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(71) Applicant (for all designated States except US): BAL-  
LARD POWER SYSTEMS INC. [CA/CA]; 9000  
Glenlyon Parkway, Burnaby, British Columbia V5J 5J9  
(CA).

**(72) Inventors; and**

(75) **Inventors/Applicants (for US only):** BOEHM, Gustav [DE/DE]; Zur Forelle 34, 88662 Ueberlingen (DE). WILKINSON, David, P. [CA/CA]; 1391 Coleman

Street, North Vancouver, British Columbia V7K 1W4 (CA). KNIGHTS, Shanna [CA/CA]; 5376 Forest Street, Burnaby, British Columbia V5G 1X2 (CA). SCHAMM, Reinhold [DE/DE]; Muensterlinger weg 12, 88179 Stetten (DE). FLETCHER, Nicholas, J. [CA/CA]; 3464 Point Grey Road, Vancouver, British Columbia V6R 1A5 (CA).

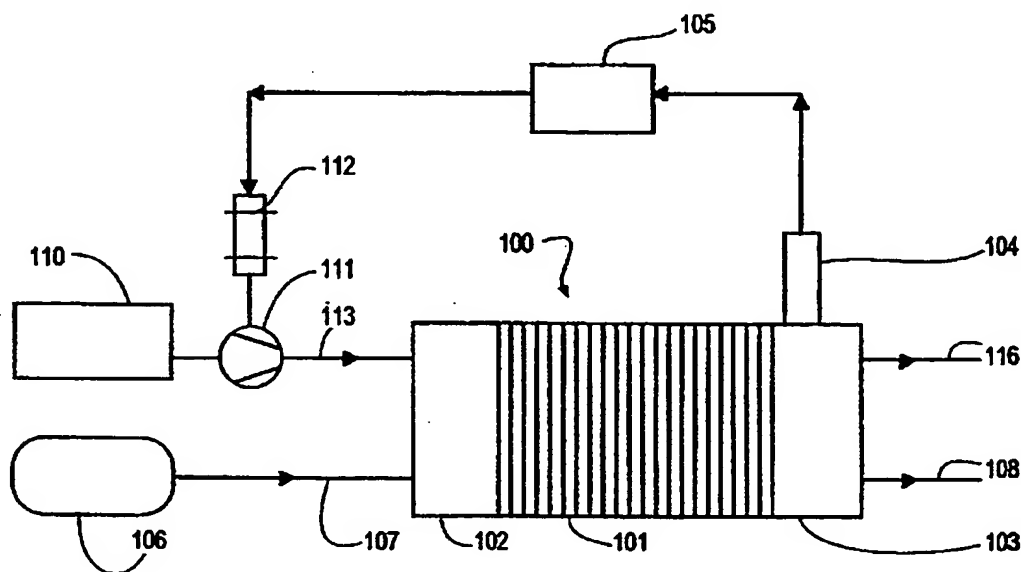
(74) Agent: DE KOCK, Elbie, R.; Russell Reyneke, Two Bentall Centre, Suite 700, 555 Burrard Street, Vancouver, British Columbia V7X 1M8 (CA).

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**(54) Title: METHOD AND APPARATUS FOR OPERATING A FUEL CELL**



**(57) Abstract:** The present invention relates to improving the overall efficiency of a fuel cell system by reducing parasitic power consumption. In particular, efficiency is improved by controlling the supply of oxidant to reduce excess oxidant stream flow by operating the fuel cell system with an oxidant stoichiometry between about one and two. A controller is programmed to decrease oxidant stoichiometry until oxidant starvation is detected or until oxidant stoichiometry is about one. When oxidant starvation is detected, the oxidant stoichiometry is increased until oxidant starvation is no longer detected. The fuel cell system employs a sensor for detecting an operational characteristic such as voltage output, or oxygen or hydrogen concentration in the cathode exhaust stream. The controller uses the operational characteristic to calculate oxidant stoichiometry or to determine when there is oxidant starvation at the cathode.

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## METHOD AND APPARATUS FOR OPERATING A FUEL CELL

### Field Of The Invention

10       The present invention relates to a method and apparatus for operating a fuel cell that improves the overall efficiency of the fuel cell system. In particular, efficiency is improved by controlling the supply of oxidant so as to reduce  
15       excess oxidant flow.

### Background Of The Invention

      Electrochemical fuel cells convert reactants, namely, fuel and oxidant fluid streams, to  
20       generate electric power and reaction products. Electrochemical fuel cells generally employ an electrolyte disposed between two electrodes, namely a cathode and an anode. The electrodes each comprise an electrocatalyst disposed at the  
25       interface between the electrolyte and the electrodes to induce the desired electrochemical reactions.

      The fuel fluid stream, which is supplied to the anode, typically comprises hydrogen and may be  
30       pure gaseous hydrogen or a dilute hydrogen stream such as a reformat stream. Alternatively, other fuels such as methanol or dimethyl ether may be supplied to the anode where such fuels may be directly oxidized. The oxidant fluid stream,  
35       which is supplied to the cathode, typically comprises oxygen, and may be pure gaseous oxygen, or a dilute oxygen stream such as air.

      For a fuel cell, reactant stoichiometry is defined herein as the ratio of the reactant  
40       supplied over the reactant theoretically required

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5 to produce the current produced by the fuel cell.  
For conventionally operated fuel cells which  
typically supply a surplus of oxidant to the  
cathode, since the oxidant is preferentially  
reduced at the cathode, oxidant stoichiometry is  
10 commonly expressed as the ratio of the oxidant  
supplied over the oxidant consumed. However, at  
lower stoichiometries, the reduction of oxidant  
may not be responsible for all of the current  
produced by the fuel cell. Other reactions, such  
15 as, for example, the reduction of protons may also  
occur at the cathode and contribute to the current  
output (i.e. with the consequence of reduced  
output voltage). In this example, while oxidant  
may still be the main component being reduced at  
20 the cathode, the amount of oxidant theoretically  
required to produce the current output may be  
higher than the amount of oxidant actually  
supplied. Therefore, when components other than  
the oxidant are reduced at the cathode, oxidant  
25 stoichiometries less than one may be sustained.  
If the oxidant is a dilute oxidant stream such as  
air, only the reactant component, namely oxygen,  
is considered in the calculation of stoichiometry  
(that is, oxidant stoichiometry is the ratio of  
30 the amount of oxygen supplied over the theoretical  
amount of oxygen required to produce the fuel cell  
output current).

Hydrogen and oxygen are reactive in the fuel  
cell and are particularly reactive with each  
35 other. Accordingly, in solid polymer fuel cells,  
an important function of the membrane electrolyte  
is to keep the hydrogen supplied to the anode



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5 separated from the oxygen supplied to the cathode.  
In addition, the membrane is proton conductive and  
functions as an electrolyte.

The overall efficiency of a fuel cell system  
is a function of the total power output of the  
10 fuel cell(s) and the parasitic power consumption.  
Total parasitic power consumption is defined  
herein as the sum of all power that is consumed by  
the fuel cell system in the course of generating  
electrical power. The net electrical power output  
15 is the total power output minus the total  
parasitic power consumption. Therefore, overall  
efficiency may be improved by reducing the  
parasitic power consumption.

One source of parasitic power consumption,  
20 for example, is the oxidant delivery subsystem  
that typically employs a mechanical device such as  
a compressor, fan, pump, rotary piston blower, or  
an equivalent mechanical device that consumes  
power to supply oxidant to the fuel cell. Higher  
25 oxidant stoichiometries generally result in higher  
parasitic power consumption because more power is  
generally required to deliver more oxidant to the  
cathode. Conventional fuel cell systems typically  
operate with an oxidant stoichiometry greater than  
30 two (2.0). Since conventional fuel cell systems  
direct at least twice the amount of oxygen to the  
cathode than is actually required to satisfy the  
electrical power demand, a significant amount of  
the parasitic power consumption is for directing  
35 surplus oxygen to the cathode. Further, fuel cell  
systems commonly employ a dilute oxidant stream.  
A dilute oxidant stream is defined herein as a

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5 fluid stream that comprises less than 100%  
oxidant. For example, air is a dilute oxidant  
stream that typically comprises about 20% oxygen,  
in addition to other components such as nitrogen.  
Accordingly, when air is employed as the dilute  
10 oxidant stream, parasitic power consumption is  
amplified because in addition to the surplus  
oxygen, the oxidant delivery subsystem must also  
supply a proportionate amount of the other non-  
reactive components.

15 One reason why the parasitic power  
consumption associated with high oxidant  
stoichiometries is tolerated, is that excess  
oxidant is desired at the cathode to avoid oxidant  
starvation at the cathode electrocatalyst.  
20 Oxidant starvation is defined herein as the status  
when oxidant stoichiometry is less than one.  
Oxygen starvation typically results in a  
condition, in the absence of oxidant at the  
cathode electrocatalyst, favoring the production  
25 of molecular hydrogen from protons and electrons  
at the cathode. In severe cases of oxidant  
starvation the fuel cell may generate a negative  
voltage and this condition is known as cell  
reversal. Oxidant stream delivery systems are  
30 typically designed to provide a generous surplus  
of oxidant to maintain performance, to reduce the  
likelihood of oxidant starvation, and to reduce  
the likelihood of hydrogen production at the  
cathode, even though this results in the  
35 aforementioned amplified parasitic power  
consumption.

In fuel cells, oxidant starvation is most

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5 likely to occur in regions furthest downstream  
from the cathode inlet where the oxidant stream  
enters the cell, for example, near the cathode  
outlet. An oxidant stoichiometry that provides a  
surplus of oxidant to the fuel cell provides an  
10 adequate concentration of oxidant to the  
electrocatalyst throughout the electrochemically  
active area of the cathode, including near the  
cathode outlet.

Another reason why conventional fuel cell  
15 systems seek to avoid low oxidant stoichiometries  
is that the temperature within the fuel cell may  
rapidly increase when oxidant stoichiometry is too  
low. It is generally desirable to maintain the  
temperature of solid polymer fuel cells below  
20 100°C. When the temperature increases within the  
fuel cell, parasitic power consumption increases  
because of the higher load on the cooling system,  
offsetting, to some degree, the reduction in  
parasitic power consumption associated with  
25 operating at a lower oxidant stoichiometry.  
Another disadvantage of operating a fuel cell  
system with a high oxidant stoichiometry is that  
higher oxidant stoichiometries generally require  
higher speeds for the mechanical devices used by  
30 the oxidant delivery subsystem to supply the  
oxidant stream to the cathode. Now that fuel cell  
systems are being developed for commercial use,  
mechanical considerations over the planned  
lifetime of commercial fuel cell systems are a  
35 factor. A mechanical disadvantage of conventional  
high stoichiometry methods of operation is that  
such methods may result in increased wear and more

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5 frequent maintenance. If the oxidant is air, there may be additional operational costs because supplying a high surplus of oxidant also results in higher flow rates that may increase air filter maintenance and/or reduce filter efficiency.

10

#### Summary of the Invention

A method of operating a fuel cell system controls oxidant stoichiometry to reduce parasitic power consumption to improve overall efficiency, while avoiding low oxidant stoichiometries that might cause reduced performance, cell reversal, hydrogen production at the cathode, and increased heat generation within the fuel cell. The fuel cell system comprises a fuel cell power generating subsystem having at least one fuel cell, and an oxidant delivery subsystem that comprises at least one mechanical device for supplying an oxidant stream to a cathode of the fuel cell. The fuel cell also has an anode supplied with a fuel stream. In a preferred embodiment, the fuel cell is a solid polymer fuel cell.

The method comprises controlling the mechanical device, to reduce parasitic power consumption by reducing the oxidant stoichiometry until  $dV/d(OS)$  is greater than a predetermined value ("PV"), where  $dV$  is the change in cell voltage and  $d(OS)$  is the change in oxidant stoichiometry (that is, the slope of a plot of voltage as a function of oxidant stoichiometry). Cell voltage is measured in volts and oxidant stoichiometry is a unit-less ratio.

To practice the invention, the value of

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5      $dV/d(OS)$  need not actually be calculated if a  
relationship between  $dV/d(OS)$  and another  
operational characteristic is known. For example,  
in preferred embodiments, an operational  
characteristic that correlates to  $dV/d(OS)$  and/or  
10     oxidant stoichiometry may be monitored. The fuel  
cell system is controlled to take action when the  
value of the monitored operational characteristic  
correlates to when  $dV/d(OS)$  is equal to or greater  
than PV. For example, in a typical fuel cell  
15     system, during normal operation, current density  
is kept constant and when oxidant stoichiometry is  
being reduced, a particular cell voltage  
correlates to when  $dV/d(OS)$  increases to PV. That  
is, when cell voltage decreases below a threshold  
20     voltage, this is determined when  $dV/d(OS)$  is  
higher than PV. Accordingly, a fuel cell system  
may be operated to reduce parasitic power  
consumption by controlling the oxidant delivery  
subsystem to maintain voltage output within a  
25     predetermined voltage range which typically  
corresponds to an oxidant stoichiometry range  
between about one and two, wherein PV is selected  
so that  $dV/d(OS)$  equals PV at the lower limit of  
the selected voltage range. The preferred range  
30     for oxidant stoichiometry may actually change  
according to the instantaneous operating  
conditions. For example, when a fuel cell is  
operating in an idle or low output condition, a  
higher oxidant stoichiometry may be preferred to  
35     prevent accumulation of water at the cathode.  
Accordingly, the value of PV may be dynamic.

The characteristics of the fuel cell and/or

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5 the type of reactants may also influence the preferred oxidant stoichiometry range. For example, in a direct methanol fuel cell, higher stoichiometries are typically employed, but the reactant supply may still be controlled to prevent  
10  $dV/d(OS)$  from increasing to higher than PV (although for a direct methanol fuel cell, PV will correspond to a higher stoichiometry, compared to a fuel cell which is fed hydrogen gas or reformat as the fuel stream).

15 Similarly, when current density is constant and oxidant stoichiometry is being reduced, a particular oxidant stoichiometry correlates to when  $dV/d(OS)$  increases to PV. Accordingly, operational characteristics, such as the oxygen  
20 concentration in the cathode exhaust stream, which correlate to oxidant stoichiometry, may be monitored to determine when oxidant stoichiometry is reduced to a value which correlates to when  $dV/d(OS)$  increases to greater than or equal to PV.  
25 The oxidant concentration in the oxidant supply stream is typically known, but if the oxidant supply stream has a variable oxidant concentration (for example, if an oxidant enrichment system is employed), the method may further comprise  
30 monitoring and measuring the oxidant concentration in the oxidant supply stream, in addition to monitoring and measuring the oxidant concentration in the oxidant exhaust stream. Alternatively, oxidant stoichiometry may be determined by  
35 monitoring and measuring a different operational characteristic, such as, for example, current output for the fuel cell power generating

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5 subsystem, which, in addition to the oxidant concentration in the oxidant exhaust stream may be used to calculate oxidant stoichiometry.

The value of  $dV/d(OS)$  generally increases as oxidant stoichiometry and cell voltage both  
10 decrease. In one embodiment, PV corresponds to when oxidant starvation is beginning to occur or when oxidant starvation is beginning to cause a decline in performance. In a more preferable embodiment, PV corresponds to when further  
15 reductions in oxidant stoichiometry will cause a sharp decline in cell voltage output, for example, when  $dV/d(OS)$  is higher than 0.02 volts.

Preferably, PV is between 0.3 volt and 7.0 volts, so that the fuel cell system operates mostly when  
20  $dV/d(OS)$  is less than PV. The selected value for PV controls the oxidant stoichiometry so that it is kept between about one and two during normal operation and closer to about one or a predetermined target value, preferably between 1  
25 and 1.5, during steady state operation.

In a preferred apparatus for practising the method, the fuel cell is one of a plurality of fuel cells arranged in a stack. When the method is applied to a fuel cell stack, the sensor may  
30 monitor the operational characteristic for one or more individual fuel cells and/or for the stack as a whole. The sensor may thus be located to monitor an operational characteristic (for example, oxidant or hydrogen concentration) within  
35 a portion of a reactant passage (for example, an internal cathode exhaust passage) that is disposed between the outside end surfaces of the stack end

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5 plates.

The oxidant stoichiometry is preferably controlled by controlling the oxidant stream mass flow rate, for example, by controlling the speed of a mechanical device, such as a compressor, a fan, a pump, or a blower. Reducing the speed of the mechanical device generally reduces parasitic power consumption and reduces oxidant stoichiometry. However, alternate methods of controlling oxidant stoichiometry may be employed which also reduce parasitic power consumption. For example, if an oxidant enrichment subsystem is employed, oxidant stoichiometry may be controlled by increasing or decreasing the concentration of oxidant in the oxidant stream supplied to the cathode(s) of the fuel cell power generating subsystem. Another method of controlling oxidant stoichiometry is adjusting the electrical power output of the fuel cell, wherein reducing power output generally increases oxidant stoichiometry.

25 A preferred method that employs a hydrogen sensor (the "Hydrogen Sensor Method") comprises:

- (a) monitoring a cathode exhaust stream downstream of the cathode to detect hydrogen gas concentration; and
- 30 (b) decreasing oxidant stoichiometry when the hydrogen gas concentration is less than a first threshold concentration.

The Hydrogen Sensor Method may further comprise increasing the oxidant stoichiometry when the hydrogen concentration is higher than a second threshold concentration (for example, 20 ppm of hydrogen), which correlates to operating



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5 conditions which are indicative of actual or  
potential oxidant starvation. The first threshold  
concentration may be, for example, the lower  
detection limit of the hydrogen sensor that is  
used to monitor the cathode exhaust stream. The  
10 second threshold concentration is greater than the  
first threshold concentration. When the hydrogen  
concentration is between the first and second  
threshold concentrations, the controller does not  
take any action to adjust the oxidant  
15 stoichiometry.

A problem with using the hydrogen  
concentration measured in the cathode exhaust  
stream to detect oxidant starvation is that  
oxidant starvation is not the only possible cause  
20 for hydrogen gas being detected at the cathode.  
For example, when the fuel comprises hydrogen,  
holes or cracks may form in the membrane or seals  
and permit reactants to "cross over" from the  
anode side to the cathode side, and vice versa.  
25 If significant reactant crossover is detected, the  
conventional response is to shut down the fuel  
cell so that it may be repaired or replaced. Fuel  
crossover and oxidant starvation may both cause  
reduced fuel cell performance, but the detection  
30 of one condition requires a response which is  
different from the response required for the other  
condition. Oxidant starvation causing hydrogen to  
be produced at the cathode generally requires the  
oxidant stoichiometry to be increased, whereas  
35 fuel crossover, if significant, may require the  
fuel cell to be shut down. Therefore, for  
appropriate action to be taken, it is desirable

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5 for the controller to be able to distinguish  
between oxidant starvation and fuel crossover when  
the fuel comprises hydrogen. The following  
embodiments of the Hydrogen Sensor Method provide  
procedures for distinguishing between oxidant  
10 starvation and fuel crossover.

The Hydrogen Sensor Method may further  
comprise steps for reducing the hydrogen gas  
concentration within the cathode exhaust stream  
when the hydrogen gas concentration is greater  
15 than a second threshold concentration, wherein the  
steps comprise comparing the oxidant stream mass  
flow rate to a maximum desired mass flow rate, and

(a) if the oxidant stream mass flow rate is  
less than the maximum desired mass flow  
20 rate, increasing the oxidant mass flow  
rate (that is, if raising the oxidant  
mass flow rate results in less hydrogen  
being detected at the cathode, then it  
is confirmed that oxidant starvation was  
25 likely the reason for hydrogen being  
detected; if oxidant starvation is not  
the source of the hydrogen at the  
cathode, the oxidant stream mass flow  
rate will quickly increase to the  
30 maximum desired mass flow rate and the  
controller will determine that fuel  
crossover is the likely hydrogen  
source); and

(b) if the oxidant mass flow rate is already  
35 greater than or equal to the maximum  
desired mass flow rate,  
ceasing operation of the fuel cell if

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5 the hydrogen gas concentration is greater  
than a third concentration threshold which is  
greater than the first and second  
concentration thresholds (that is, since the  
oxidant stream mass flow rate is already at,  
10 or exceeds, the desired maximum, oxidant  
starvation is not the likely source of the  
hydrogen in the cathode exhaust stream; since  
the hydrogen concentration is above the third  
threshold, this indicates that there may be  
15 an excessive amount fuel passing through  
leaks between the anode and cathode); and  
generating a warning signal and  
continuing to operate the fuel cell if the  
hydrogen gas concentration is less than the  
20 third concentration threshold (i.e. that is,  
the value of the third threshold is selected  
so that the fuel cell system can be safely  
operated when the hydrogen concentration in  
the cathode exhaust stream is less than the  
25 third threshold).

The Hydrogen Sensor Method may further  
comprise continuously monitoring the cathode  
exhaust stream for the hydrogen gas concentration  
and determining whether the hydrogen gas  
30 concentration is increasing or decreasing, and  
when the hydrogen gas concentration is greater  
than a second threshold concentration, the method  
further comprises:

maintaining a substantially constant  
35 oxidant stoichiometry when the hydrogen  
concentration is decreasing; and  
increasing the oxidant stoichiometry

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5           when the hydrogen concentration is  
          increasing.

          In addition to monitoring whether hydrogen  
concentration is increasing or decreasing, when  
the hydrogen gas concentration is greater than a  
10       second threshold concentration, the method may  
also comprise additional steps to determine  
whether the source of the hydrogen is oxidant  
starvation or fuel crossover. For example, the  
additional steps may comprise:

15           measuring fuel cell voltage and  
          comparing it to a voltage threshold value  
          (for a Ballard<sup>7</sup> MK V fuel cell, the voltage  
threshold value could be, for example, 100  
millivolts), and

20           if the fuel cell voltage exceeds  
          the voltage threshold value and the  
hydrogen gas concentration is  
increasing, decreasing the pressure of  
the fuel stream (in this case, since  
25       voltage exceeds the threshold value, the  
reason for the increasing hydrogen  
concentration is probably a leak; to  
reduce the effect of the leak, the  
method preferably comprises controlling  
30       the fuel stream pressure so that it is  
less than or equal to the pressure of  
the oxidant stream);

          if the fuel cell voltage is less  
than the voltage threshold value, the  
35       hydrogen gas concentration is  
increasing, and oxidant mass flow rate  
is less than a desired maximum, then

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5           increasing the oxidant stoichiometry (in  
this case, since oxidant mass flow rate  
is less than the desired maximum, the  
cause for the low cell voltage and the  
presence of hydrogen gas may be oxidant  
10          starvation, and the controller attempts  
to correct this condition by increasing  
the oxidant stoichiometry); and

          if the fuel cell voltage is less  
than the voltage threshold value, the  
15          hydrogen gas concentration is  
increasing, and oxidant mass flow rate  
is greater than or equal to a desired  
maximum, then decreasing the pressure of  
the fuel stream (in this case, the low  
20          cell voltage may be caused by oxidant  
starvation or fuel leaking from the  
anode to the cathode; since the oxidant  
mass flow rate is already greater than  
or equal to the desired maximum, the  
25          pressure of the fuel stream is reduced,  
thereby reducing fuel cell power output  
and oxygen consumption at the cathode,  
to counter oxidant starvation and reduce  
the effect of any leaks).

30          Further additional steps may be taken to  
confirm whether the detected hydrogen gas  
concentration is caused by oxidant starvation or  
fuel crossover. For example, the method may also  
comprise regulating fluid pressure of the oxidant  
35          and fuel streams to increase or decrease a  
pressure differential between the oxidant and fuel  
streams to help determine whether the hydrogen

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5 measured at the cathode is caused by a leak or by  
oxidant starvation. If the change in the pressure  
differential has a significant effect on the  
measured hydrogen concentration, then it can be  
determined that there is a significant problem  
10 with hydrogen crossover.

For any of the above-described methods, the  
oxidant stoichiometry is typically adjusted by  
controlling the speed of the oxidant compressor or  
blower. However, other methods of changing the  
15 oxidant stoichiometry may also be used, such as  
adjusting the oxidant concentration in the oxidant  
supply stream or changing the electrical power  
output of the fuel cell without changing the mass  
flow rate of the oxidant supply stream. When the  
20 oxidant stream mass flow rate is adjusted, it is  
typically changed by a fixed amount or by a fixed  
percentage of the instant oxidant stream mass flow  
rate. Alternatively, oxidant stoichiometry may be  
adjusted by adjusting the oxidant stream mass flow  
25 rate by an amount that is dependent upon the  
magnitude of the detected hydrogen gas  
concentration. For example, the controller may be  
programmed to reduce the oxidant stoichiometry by  
a larger amount when a large surplus of oxygen is  
30 detected compared to when only a small surplus of  
oxygen is detected.

The method of controlling the oxidant  
delivery subsystem to reduce parasitic power  
consumption may comprise calibrating an oxidant  
35 delivery subsystem for a fuel cell. For example,  
the calibration method may comprise:

(a) operating the fuel cell at a particular

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- 5                   electrical power output;
- (b) supplying an oxidant stream to a cathode  
of the fuel cell;
- (c) adjusting the operating speed of a  
mechanical oxidant delivery device;
- 10           (d) measuring an operational characteristic  
that corresponds to  $dV/d(\text{oxidant stoichiometry})$ ; and
- (e) recording as the desired operating speed  
for said particular electrical power  
15           output, said operating speed when said  
 $dV/d(\text{oxidant stoichiometry})$  is equal to  
a predetermined value.

The calibration method may be repeated for a  
plurality of electrical power outputs so that the  
20           desired operating speed for the mechanical oxidant  
delivery device may be determined and recorded in  
a look-up table for many different electrical  
power demands. The desired operating speed may  
then be determined by referring to a look-up table  
25           for the operating speed that corresponds to the  
instant electrical power demand.

An advantage of the calibration method is  
that it may be used throughout the operating life  
of the fuel cell to adjust for changes in the fuel  
30           cell over time. For example some of the fuel cell  
properties may be subject to degradation over time  
and that may change the stoichiometry requirements  
over the operational lifetime of the fuel cell.

The present method and apparatus also  
35           controls the amount of oxidant supplied to a fuel  
cell stack and reduces system inefficiencies  
caused by the over-supply of oxidant. Preferably,

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5 the method also controls the oxidant delivery subsystem to increase the oxidant stoichiometry to avert oxidant starvation conditions. Accordingly, a method of operating a fuel cell is provided that detects when the oxidant stoichiometry may be  
10 decreased or increased, and when the flow of oxidant should be discontinued altogether.

The present method may also be employed to operate a fuel cell and further reduce parasitic power consumption by controlling the supply of  
15 fuel to reduce excess fuel flow. The same principles that apply to the present method for controlling the oxidant supply apply to a method for controlling the fuel supply. Fuel cells typically employ a mechanical device, such as, for  
20 example, a compressor or pump, to supply a fuel stream to the anode(s) of the fuel cell(s). Therefore, parasitic power consumption may be reduced by reducing fuel stoichiometry to reduce the amount of excess fuel supplied to the fuel  
25 cell anode(s) and the work performed by the compressor. A reduction of the fuel stoichiometry generally causes an increase in  $dV/d(\text{fuel stoichiometry})$ . According to the present method, fuel stoichiometry is kept within a predetermined range by reducing fuel stoichiometry until  
30  $dV/d(\text{fuel stoichiometry})$  increases above a predetermined threshold value. The predetermined range and threshold value depend upon the particular characteristics and operating  
35 conditions of each particular fuel cell or fuel cell stack. The predetermined range may be empirically determined, for example, with



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5 consideration to these factors.

Generally, it is desirable to reduce reactant stoichiometry until  $dV/d(\text{reactant stoichiometry})$  is greater than about 0.02 volt. More preferably, the predetermined value for  $dV/d(\text{reactant}$   
10  $\text{stoichiometry})$  is between 0.30 and 7.0 volts. The voltage drop is generally more severe with fuel starvation, compared to oxidant starvation and when cell voltage is one of the monitored characteristics, this effect may be used to help  
15 differentiate between oxidant or fuel starvation.

#### Brief Description Of The Drawings

The advantages, nature and additional features of the invention will become more  
20 apparent from the following description, together with the accompanying drawings, in which:

FIG. 1 is a schematic diagram of a fuel cell system comprising a detector for detecting oxidant starvation at the cathode and a controller for  
25 processing information from the detector and controlling the oxidant delivery subsystem to increase or decrease the oxidant stoichiometry;

FIGs. 2a, 2b and 2c are plots of experimental data that illustrate the effect oxidant  
30 stoichiometry has on operational characteristics such as voltage output, heat produced, and  $dV/d(\text{oxidant stoichiometry})$ . FIG. 2a is a plot of fuel cell voltage output as a function of oxidant stoichiometry for a solid polymer fuel cell  
35 operating at a current density of 500 amps per square foot (about 540 milliamps per square centimeter), during normal operation. FIG. 2b is a

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5 plot of fuel cell voltage output and  $dV/d(\text{oxidant stoichiometry})$  as a function of oxidant stoichiometry for the same fuel cell experiment as FIG. 2a. FIG. 2c is a plot of  $dV/d(\text{oxidant stoichiometry})$  as a function of oxidant  
10 stoichiometry for a fuel cell stack comprising four fuel cells;

FIGs. 3a, 3b and 4-12 are logic diagrams illustrating various preferred embodiments of a the present method of operating a fuel cell and  
15 controlling the oxidant stoichiometry. In FIGs. 3a, 3b and 4-11, the logic diagrams illustrate a method of adjusting the oxidant stream mass flow rate to adjust the oxidant stoichiometry. In these embodiments, the oxidant stream mass flow  
20 rate may also be changed in response to changes in power output, with the illustrated method being used to adjust the oxidant stream mass flow rate and hence oxidant stoichiometry to prevent oxidant starvation and reduce parasitic power losses  
25 associated with supplying excess oxidant. In FIG. 12 the logic diagram illustrates a method of calibrating a fuel cell system to determine the desired oxidant stream mass flow rate to produce a particular power output at a predetermined oxidant  
30 stoichiometry.

#### Detailed Description Of Preferred Embodiments

FIG. 1 is a schematic diagram that shows the fuel cell power generating subsystem, the oxidant  
35 delivery subsystem, and the fuel delivery subsystem of a fuel cell system. The fuel cell power generating subsystem comprises a fuel cell

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5 stack 100, comprising a plurality of fuel cells  
101 interposed between end plates 102 and 103.  
The fuel cell power generating subsystem further  
comprises sensor 104. When fuel cell stack 100 is  
operating, sensor 104 measures an operational  
10 characteristic that correlates to  $dV/d(OS)$ . For  
example, when fuel cell stack 100 is operating at  
a constant current density, sensor 104 may measure  
an operational characteristic which relates to  
oxidant stoichiometry, cell voltage, or a  
15 characteristic which is typically detected when  
oxidant starvation is occurring at the fuel cell  
cathode.

Sensor 104 outputs a signal to controller 105  
which processes the signal to determine when  
20  $dV/d(OS)$  is within the desired operating range and  
when oxidant stoichiometry should be adjusted so  
that  $dV/d(OS)$  is restored to the desired operating  
range. For example, oxidant stoichiometry may be  
increased if the measured operational  
25 characteristic indicates an oxidant stoichiometry  
and/or the presence of conditions at the cathode  
which indicates actual, or a potential for,  
oxidant starvation. Preferably, the desired  
operating range prevents any oxidant starvation at  
30 the cathode that inhibits the fuel cell from  
producing the desired power output.

When the operational characteristic monitored  
by sensor 104 is the concentration of a gas in the  
cathode exhaust stream, sensor 104 may comprise a  
35 sensing element that is located within the  
interior of the cathode exhaust passage so that it  
is exposed to the cathode exhaust stream. The

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5 portion of the cathode exhaust passage where the sensing element is located may be a manifold or fluid passage internal to fuel cell stack 100, or in cathode exhaust passage 116.

10 In one embodiment, oxidant stoichiometry is controlled by using sensor 104 to measure an operational characteristic that correlates to oxidant stoichiometry. In another embodiment, sensor 104 detects an operational characteristic that is indicative of oxidant starvation at the  
15 cathode so that the oxidant stoichiometry may be controlled to reduce the amount of excess oxidant supplied to fuel cell stack 100, while preventing harmful oxidant starvation at the fuel cell cathodes (that is, in this embodiment controller  
20 105 increases oxidant stoichiometry when sensor 104 detects actual or potential oxidant starvation and may decrease oxidant stoichiometry when oxidant starvation is not detected). In yet another embodiment, controller 105 checks for  
25 oxidant starvation while maintaining  $dV/d(OS)$  within a predetermined operating range; if oxidant starvation is detected, oxidant stoichiometry is increased until oxidant starvation is no longer detected, even though this may result in  
30 temporarily raising  $dV/d(OS)$  above the desired operating range.

The fuel delivery subsystem supplies a fuel stream from fuel supply 106 to the anodes of fuel cell stack 100 via fuel supply passage 107. When  
35 the fuel stream is a compressed gas, such as substantially pure hydrogen, fuel supply 106 may comprise a pressure vessel and a pressure control

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5 valve (not shown) for regulating the pressure of  
the fuel stream supplied to fuel cell stack 100.  
Alternatively, the fuel may be a liquid fuel such  
as methanol and fuel supply 106 may comprise a  
fuel tank. Liquid fuel may be supplied directly  
10 to fuel cell stack 100 (that is, a so called  
"liquid feed fuel cell"). Alternatively, fuels  
such as methanol, natural gas, or other  
hydrocarbons may be further processed to produce a  
gaseous hydrogen-containing reformat stream, in  
15 which case fuel supply 106 further comprises a  
fuel processor. When the fuel storage tank is not  
pressurized, the fuel delivery subsystem may  
further comprise a compressor or pump for  
controlling the pressure and mass flow rate of the  
20 fuel stream supplied to fuel cell stack 100.  
After the fuel stream has been directed to the  
anodes of fuel cell stack 100 to participate in  
the desired electrochemical reactions, a fuel-  
depleted fuel exhaust stream is exhausted from  
25 fuel cell stack 100 via fuel exhaust passage 108.

In the preferred embodiment illustrated by  
FIG. 1, the oxidant delivery subsystem comprises  
oxidant supply 110, mechanical device 111 for  
raising the pressure of the oxidant supply stream,  
30 and electric motor 112 coupled to mechanical  
device 111 for providing power thereto. Oxidant  
supply 110 may comprise a vessel for holding a  
supply of oxidant, but more typically, oxidant  
supply 110 comprises an air intake for receiving  
35 and filtering air from the surrounding atmosphere.  
From oxidant supply 110, the oxidant supply stream  
is directed to mechanical device 111, which

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5 raises the pressure of the oxidant stream. The pressurized oxidant supply stream is directed to the fuel cell power generating subsystem via oxidant supply passage 113.

10 Controller 105 receives an output signal from sensor 104. The output signal is processed by controller 105 to determine whether  $dV/d(OS)$  is within the desired operating range. Controller 105 communicates with the oxidant delivery subsystem to control the output of mechanical  
15 device 111 to maintain  $dV/d(OS)$  within a predetermined desired operating range (which preferably corresponds to an oxidant stoichiometry between about one and two).

For example, in the embodiment illustrated in  
20 FIG. 1, controller 105 controls electric motor 112 to control the speed of mechanical device 111. Mechanical device 111 is typically a compressor such as a rotary piston compressor or a reciprocating piston compressor. However, other  
25 types of mechanical devices may also be employed such as, for example a pump, a fan, or a blower. Mechanical device 111 raises the pressure of the oxidant supply stream to provide sufficient energy for directing the desired oxidant mass flow rate  
30 to the fuel cell cathodes within fuel cell stack 100. After the cathodes, the oxygen-depleted oxidant stream is ultimately exhausted from fuel cell stack 100 through cathode exhaust passage 116.

35 In a preferred method, during steady state operation, controller 105 controls the oxidant delivery subsystem so that the value of  $dVx/d(OS)$

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5 corresponds to operating conditions when oxidant stoichiometry is close to about one. Steady state operation is defined herein as an operational mode for the fuel cell system when the power output of fuel cell stack 100 is substantially constant.

10 During normal operation, when the power demand is dynamic, controller 105 may allow  $dV/d(OS)$  to vary within a predetermined desired operating range that preferably corresponds to when oxidant stoichiometry is between about one and two.

15 Normal operation is defined herein to exclude start-up and shut-down modes when controller 105 may allow a value for  $dV/d(OS)$  that corresponds to higher or lower oxidant stoichiometries, respectively. According to a preferred method, parasitic power demands are reduced during normal  
20 operation by reducing the power consumption of the oxidant delivery subsystem, by keeping oxidant stoichiometry less than two and preferably close to about one during steady state operation.

25 In a first preferred embodiment, sensor 104 measures the voltage output from fuel cell stack 100. During normal operation, at constant current density, fuel cell voltage output correlates to oxidant stoichiometry, so if sensor 104 measures  
30 fuel cell voltage output, sensor 104 may be used to determine oxidant stoichiometry and  $dV/d(OS)$ . For example, plot A of FIG. 2a sets forth the voltage output (left y-axis) as a function of oxidant stoichiometry (x-axis) for a fuel cell  
35 operating at a constant current density of 500 amps per square foot (about 540 milliamps per square centimeter). That is, if at least one of

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5 cell voltage output or oxidant stoichiometry is known, then  $dV/d(OS)$  may be determined by referring to plot A. Plot C of FIG. 2b sets forth voltage output as a function of oxidant stoichiometry, and plot D of FIG. 2b sets forth  
10  $dV/d(OS)$  as a function of oxidant stoichiometry. Plot D of FIG. 2b shows that by selecting a predetermined threshold value for  $dV/d(OS)$ , oxidant stoichiometry may be reduced until it approaches one, without significant sacrifices to  
15 performance, as long as oxidant stoichiometry is increased when  $dV/d(OS)$  is greater than or equal to the predetermined threshold value. For example, for the fuel cell of FIG. 2b, a predetermined threshold value for  $dV/d(OS)$  could be a value  
20 between 0.02 and 0.3. For a threshold value of 0.3, oxidant stoichiometry could be reduced to about 1.2 before  $dV/d(OS)$  would increase to above about 0.3; at this point voltage output is still higher than 0.6 volts so fuel cell performance is  
25 not significantly compromised.

In the example of FIGs. 2a and 2b, the fuel cell was a Ballard<sup>TM</sup> MK V fuel cell which employed a solid polymer ion exchange membrane made from Nafion<sup>®</sup> 117 (a co-polymer of tetrafluoroethylene and perfluorovinylether sulfonic acid). The  
30 electrodes were made from carbon fiber paper with a thickness of 0.09 inch (about 2.29 mm) obtained from Toray Industries Inc. The catalyst layer on the electrodes was platinum black catalyst mixed with a tetrafluoroethylene binder. The catalyst  
35 loading on each electrode was 4 mg/cm<sup>2</sup>.

In the example of FIGs. 2a and 2b, if fuel



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5 cell voltage output is monitored,  $dV/d(OS)$  itself need not be monitored, since the relationship between voltage output and  $dV/d(OS)$  may be determined (see, for example, FIG. 2b). Accordingly, the oxidant delivery subsystem may be  
10 controlled to maintain voltage output between about 0.63 volt and about 0.67 volt, then oxidant stoichiometry will be maintained between about 1.1 2 and about 1.4. That is, if sensor 104 detects a voltage output higher than 0.67 volts, controller  
15 105 controls the oxidant delivery subsystem to reduce the speed of mechanical device 111, thereby reducing parasitic power consumption, reducing oxidant stoichiometry, and keeping  $dV/d(OS)$  within the desired predetermined range. If sensor 104  
20 detects a voltage output less than 0.63 volts, then controller 105 controls the oxidant delivery subsystem to increase the speed of mechanical device 111, to lower  $dV/d(OS)$  and increase voltage output and oxidant stoichiometry, thereby  
25 preventing oxidant starvation at the fuel cell cathodes.

Persons skilled in the art will recognize that fuel cell stacks, with different features, such as, for example, the size of the  
30 electrochemically active area, may operate under the same conditions and produce different voltages from those shown in FIG. 2a. However, for any particular fuel cell or fuel cell stack, a similar relationship between voltage output and oxidant  
35 stoichiometry can be plotted and used during normal operating conditions to control oxidant stoichiometry to reduce parasitic power

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5 consumption and maintain  $dV/d(OS)$  within a desired predetermined range.

FIG. 2a also shows plot B which sets forth, for the same fuel cell, theoretical heat produced within the fuel cell (right y-axis) as a function  
10 of oxidant stoichiometry (x-axis). The theoretical amount of heat produced within the fuel cell was calculated by calculating the heat balance for the fuel cell. That is, the calculation determined the heat produced by  
15 considering the total enthalpy of the inlet and outlet fluid streams and the power produced. Plot B shows that for this particular fuel cell there is a substantial increase in the heat produced therein when the oxidant stoichiometry is between  
20 1.2 and 0.9. Because increases in temperature within a fuel cell may cause increases in parasitic power consumption by the cooling subsystem, it is important to also consider this effect when selecting the desired predetermined  
25 range for  $dV/d(OS)$ . Accordingly, for some fuel cells the desired range for  $dV/d(OS)$  may correlate to an oxidant stoichiometry range between about 1.2 and 2.0.

FIG. 2c is a plot of the data from four fuel  
30 cells that were arranged in a stack, with each fuel cell operating at a constant current density of 500 amps per square foot (about 540 milliamps per square centimeter). Plots E through H each set forth  $dV/d(OS)$  as a function of oxidant  
35 stoichiometry for a respective one of the four fuel cells in the stack. Plot I sets forth the average  $dV/d(OS)$  against oxidant stoichiometry.

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5 FIG. 2c, like FIG. 2b, shows the relationship between oxidant stoichiometry and  $dV/d(OS)$ , and how  $dV/d(OS)$  progressively increases as oxidant stoichiometry is reduced towards one.

10 FIG. 2c shows that, within a fuel cell stack, there may be different values for  $dV/d(OS)$  for different fuel cells. In this case, the fuel cell may be controlled with reference to the average  $dV/d(OS)$ . Alternatively, the value of  $dV/d(OS)$  for a selected fuel cell may be monitored to  
15 control the oxidant stoichiometry for an entire fuel cell stack. The selected fuel cell may be made more responsive to changes in oxidant stoichiometry so that oxidant stoichiometry may be controlled to prevent large fluctuations in fuel  
20 cell performance. For example, the selected fuel cell may be designed so that its voltage output decreases more rapidly than the voltage output of the other fuel cells in the stack, so that oxidant stoichiometry may be increased before there is a  
25 significant decrease in the voltage output of the fuel cell stack.

The logic diagrams of FIGs. 3a, 3b, and 4-12 will be explained with reference to the components of the fuel cell system shown in FIG. 1.

30 In a preferred embodiment, controller 105 may be programmed to perform the method shown in the logic diagram of FIG. 3a. In this method, controller 105 controls oxidant stoichiometry to reduce parasitic power consumption in response to  
35 signals emitted from sensor 104, by controlling oxidant stream mass flow rate using motor 112 and mechanical device 111. The method starts at step

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5 120. In step 122 reactants are supplied to fuel cell stack 100 and sensor 104 is activated. During operation of stack 100, at step 124, sensor 104 monitors at least one operational characteristic that correlates to  $dV/d(OS)$ . For  
10 example, for a fuel cell operating at a constant current density, the operational characteristic measured by sensor 104 may be fuel cell voltage output or an operational characteristic which correlates to oxidant stoichiometry, because if  
15 one of these operational characteristics is known,  $dV/d(OS)$  may be determined by referring to a plot of cell voltage as a function of oxidant stoichiometry (for example, FIG. 2a). Sensor 104 may measure the voltage output of fuel cell stack  
20 100 or the voltage output of selected individual fuel cells 101, to determine  $dV/d(OS)$  for stack 100 or individual fuel cells 101, respectively. Alternatively, sensor 104 may measure the concentration of oxygen in a cathode exhaust  
25 stream to determine oxidant stoichiometry, which correlates to  $dV/d(OS)$ . The oxygen concentration in the oxidant supply stream is known when it is pure oxygen (that is, 100%), or air (that is, about 20%). If the concentration of oxygen in a  
30 dilute oxidant supply stream is not constant, then an oxygen sensor may be used to measure the oxygen concentration upstream of fuel cell stack 100. Alternatively, if fuel cell current output and oxygen concentration in the cathode exhaust are  
35 known, controller 105 may calculate oxidant stoichiometry by determining the amount of oxygen consumed by the fuel cell to generate the

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5     electrical current.

      In another embodiment, when sensor 104 measures hydrogen concentration in the cathode exhaust stream, the detection of hydrogen above a threshold amount, (for example, 20 ppm), may  
10     indicate that a significant amount of oxidant starvation is occurring at a fuel cell cathode. In this embodiment, the concentration of hydrogen determines the severity of the oxidant starvation that correlates to an oxidant stoichiometry for  
15     the fuel cell. Accordingly, sensor 104 outputs a signal that is representative of the measured value of any operational characteristic that itself, or in combination with other factors, correlates to  $dV/d(OS)$ . The output signal from  
20     sensor 104 may thus be received and processed by controller 105 to calculate or infer  $dV/d(OS)$  so that controller 105 may control the oxidant stoichiometry to reduce parasitic power consumption.

25     In steps 126 and 128, controller 105 determines whether the operational characteristic correlates to a  $dV/d(OS)$  that is within the desired range. At step 126, if the operational characteristic correlates to a  $dV/d(OS)$  that is  
30     lower than a first predetermined value (that is, the upper limit of the desired oxidant stoichiometry range), then, at step 132 controller 105 causes the oxidant stoichiometry to be decreased. At step 128, if the operational  
35     characteristic correlates to a  $dV/d(OS)$  that is greater than a second predetermined value (that is, the lower limit of the desired

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5 oxidant stoichiometry range), then, at step 134 controller 105 causes the oxidant stoichiometry to be increased. If it is determined that the present oxidant stoichiometry is within the desired range (that is, the answer is "no" to the  
10 questions posed in both steps 126 and 128), then no steps are taken to change oxidant stoichiometry. After steps 128, 132 or 134, it is determined whether sensor 104 is still activated.

As long as sensor 104 remains activated, the  
15 method repeats by returning to step 124. If sensor 104 is no longer activated, the process stops at step 138.

The method of FIG. 3b is substantially the same as the method of FIG. 3a, with the addition  
20 of step 125, which provides for specifically checking whether or not oxidant starvation is detected. For the steps that are common to the methods of both FIG. 3b and FIG. 3a the same reference numerals are employed.

25 The desired operating range for the oxidant stoichiometry may have a lower limit that normally prevents significant oxidant starvation at the cathodes. However, localized oxidant starvation may occur, even when oxidant stoichiometry is much  
30 higher than one (for example, even when oxidant stoichiometry is within the desired operating range). Localized oxidant starvation may occur at portions of the cathode where the oxidant is prevented from accessing the catalyst, for example  
35 where access is prevented by the accumulation of water. Localized starvation conditions may result in reduced performance, lower efficiency, and

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5     undesirable hydrogen production at the cathode.  
Localized oxidant starvation is difficult to  
detect because fuel cell stack 100, as a whole,  
may have a positive voltage within the desired  
operating range, while only a portion of the  
10    cathode is oxidant starved. Efficiency may be  
improved by counter-acting localized starvation,  
for example, by temporarily increasing oxidant  
mass flow rate through the cathode to disperse  
accumulated water from the cathode.

15           Localized oxidant starvation may be detected  
by monitoring for irregularities that may be  
indicators of oxidant starvation, such as, for  
example, detecting a threshold hydrogen gas  
concentration (for example, greater than 20 ppm)  
20    in the cathode exhaust stream. The actual  
threshold hydrogen gas concentration selected for  
a particular fuel cell or fuel cell stack will  
depend upon the particular characteristics such  
as, for example, the number of fuel cells in a  
25    stack, the mass flow rate of oxidant stream, the  
type of electrolyte, and so forth. Localized  
oxidant starvation may not have a determinative  
effect on the voltage output of fuel cell stack  
100, but any degree of oxidant starvation may  
30    result in the production of hydrogen at the  
cathode. Another method of detecting a  
possibility of localized oxidant starvation in  
fuel cell stack 100 is monitoring the voltage  
output of individual fuel cells 101. If an  
35    individual fuel cell has a lower voltage output  
than the other fuel cells in stack 100, this is an  
indication that there may be a localized oxidant

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5     starvation problem (for example, caused by the accumulation of water in the cathode of the fuel cell with the low voltage output).

          According to the method of FIG. 3b, at step 125, if oxidant starvation is detected, then  
10     oxidant stoichiometry is increased at step 134. At step 125, if oxidant starvation is not detected, then the process beginning at step 126 is essentially the same as in the process of FIG. 3a.

15           FIG. 4 illustrates another method of reducing oxidant stoichiometry to reduce parasitic power consumption wherein sensor 104 monitors for an operational characteristic that is indicative of oxidant starvation at the cathode. The method of  
20     FIG. 4 starts at step 140. At step 142 an oxidant stream is supplied to a fuel cell cathode, a fuel stream is supplied to a fuel cell anode and sensor 104 is activated. At step 144 activated sensor 104 monitors for oxidant starvation at the  
25     cathode. Sensor 104 sends a signal to controller 105 that indicates when oxidant starvation is detected at the cathode. Sensor 104 may detect, for example, the voltage output of fuel cell stack 100 or selected individual fuel cells within stack  
30     100. Alternatively, sensor 104 may detect the concentration of oxygen or hydrogen in a cathode exhaust stream. For example, if no oxygen, or only a "very low concentration", is detected, this is a good indication that oxidant starvation may  
35     be occurring at the cathode. The definition of what constitutes a "very low concentration" of oxygen depends upon the operating conditions and



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5 the properties of the reactants. For example, if the inlet oxidant stream comprises about 20% oxygen, then a "very low concentration" may be 5% oxygen in the cathode exhaust stream (that is, corresponding to an overall oxidant stoichiometry of about 1.33). However, if, for example, the  
10 inlet oxidant stream comprises 30% oxygen, then a "very low concentration" may be 7% (that is, corresponding to an overall oxidant stoichiometry of about 1.30). Preferably, the concentration of oxygen selected as a threshold value corresponds  
15 to a predetermined oxidant stoichiometry, with consideration given to the oxygen concentration in the inlet oxidant stream. Similarly, if sensor 104 measures a hydrogen concentration above a  
20 threshold amount (for example, above 20 ppm), then it is likely that oxidant starvation is occurring at a fuel cell cathode. The values for the threshold concentrations depend upon the particular characteristics of the fuel cell  
25 system, such as, for example, the oxidant stream flow rate, the size of the fuel cells and the number of fuel cells in a stack.

At step 146, controller processes the signal from sensor 104 and determines whether oxidant  
30 starvation, or a likelihood of oxidant starvation, has been detected. In either case, if such a condition is detected, then the oxidant stoichiometry is increased at step 148. If, at step 146 it is determined that there is no  
35 indication of oxidant starvation at the fuel cell cathodes, then the oxidant stoichiometry is decreased at step 150.

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5       After either step 148 or 150, controller 105  
checks at step 152 whether sensor 104 is still  
activated. If sensor 104 is no longer activated,  
then the method stops at step 154. As long as  
sensor 104 remains activated, the method of  
10       controlling the oxidant stoichiometry repeats by  
returning to step 144.

      The logic diagrams of FIGs. 5-12 are directed  
to examples of methods wherein the operational  
characteristic measured by sensor 104 is the  
15       concentration of hydrogen gas in a cathode exhaust  
stream. In view of the present disclosure,  
persons skilled in the art will understand that,  
alternative operational characteristics such as,  
for example, fuel cell voltage output or oxidant  
20       concentration, may also be used in conjunction  
with the methods set out in the logic diagrams of  
FIGs. 5-12. That is, sensor 104 may be a sensor  
that measures any operational characteristic of  
the fuel cell system that may be employed by  
25       controller 105 to determine  $dV/d(OS)$  and/or the  
presence of oxidant starvation at the cathode.

      FIG. 5 is a logic diagram for a method  
wherein controller 105 determines whether to  
increase or decrease oxidant stoichiometry based  
30       upon whether the hydrogen gas concentration  
measured by sensor 104 exceeds a predetermined  
threshold concentration (TC). The method starts  
at step 160. At step 162 sensor 104 monitors the  
cathode exhaust stream for hydrogen gas. At step  
35       164 controller 105 determines whether the hydrogen  
gas concentration measured at step 162 exceeds TC.  
Minute quantities of hydrogen in the cathode

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5 exhaust stream may not be indicative of a problem. Accordingly, TC is a threshold hydrogen gas concentration that is empirically known for a particular fuel cell to be indicative of oxidant starvation at the cathodes. For example, for a  
10 Ballard7 MK V fuel cell, controller 105 may be programmed so that TC is a hydrogen concentration of 20 ppm. Until sensor 104 detects a hydrogen concentration greater than or equal to TC, controller 105 reduces oxidant stoichiometry at  
15 step 166, typically by reducing the mass flow rate of the oxidant supply stream (thereby reducing parasitic power consumption).

When sensor 104 detects a hydrogen concentration greater than TC, this is an  
20 indication that oxidant starvation is occurring (or is likely to occur) and controller 105 proceeds to step 168. At step 168, controller 105 determines whether the oxidant stream mass flow rate is greater than or equal to a desired  
25 maximum. If the oxidant stream mass flow rate is not greater than or equal to the desired maximum, then oxidant stoichiometry is increased at step 170. Normally oxidant stoichiometry is increased by controlling motor 112 to increase the speed of  
30 mechanical device 111. Alternatively, other measures may be used instead or in combination with controlling motor 112 to increase oxidant stoichiometry. For example, oxidant stoichiometry may be increased by reducing electrical power  
35 output without a corresponding reduction in oxidant stream mass flow rate.

If, however, it is determined at step 168

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5 that the oxidant stream mass flow rate is in fact greater than or equal to the desired maximum mass flow rate, then, controller 105 proceeds to step 172 and determines whether to generate a warning signal (step 174) while continuing to operate the  
10 fuel cell system, or, shut down (cease operation of) fuel cell stack 100 at step 176. At step 172, controller 105 makes its determination by considering whether the hydrogen gas concentration is higher or lower than a predetermined  
15 concentration limit (CL). CL is typically a value much greater than TC. If the hydrogen concentration is higher than CL, this indicates that a much higher than normal concentration of hydrogen is present at the cathode. For example,  
20 if the fuel is hydrogen, a significant amount of fluid leakage between the anode and cathode may cause the hydrogen concentration in the cathode exhaust stream to exceed CL, and such a condition warrants shutting the fuel cell down so that the cause of the elevated hydrogen concentration may  
25 be investigated.

If the fuel cell system comprises an array of fuel cell stacks with each stack monitored in the manner depicted in FIG. 5, then the array may  
30 continue to produce electrical power, but with one stack shut down.

As noted above, operational characteristics other than hydrogen concentration in the cathode exhaust stream may be employed instead. For  
35 example, with reference to the logic diagram of FIG. 5, alternate equivalent steps are described herein for a sensor that measures fuel cell

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5 voltage output. Alternate steps are described using the same reference numerals, but with a suffixed "a". According to the alternate method, after starting the method at step 160a, a fuel cell voltage output sensor monitors output voltage  
10 at step 162a. At step 164a, controller 105 determines if the output voltage is lower than a predetermined threshold output voltage (TOV). In this example, the predetermined TOV preferably corresponds to a condition when there is a  
15 potential for oxidant starvation at the fuel cell cathode. If voltage output is lower than TOV, the oxidant stoichiometry is increased at step 170a, but not before first checking, at step 168a, that the oxidant stream mass flow rate is not already  
20 greater than or equal to a desired maximum. If fuel cell voltage output is not less than TOV, then controller 105 decreases oxidant stoichiometry at step 166a. At step 168a, if it is determined that oxidant stream mass flow rate  
25 is greater than or equal to a desired maximum, then controller 105 proceeds to step 172a. At step 172a, if the sensor measures an output voltage that indicates cell reversal, then controller 105 shuts down the fuel cell at step  
30 176a. If cell reversal is not detected, then the fuel cell system may continue to operate, but with controller 105 generating a warning signal at step 174a.

35 FIG. 6 is a logic diagram which illustrates a method wherein controller 105 determines an appropriate action with reference to a predetermined desired oxidant stoichiometry for

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5 the instant electrical power output. The method starts at step 180 with the supply of reactants to fuel cell stack 100 and activation of sensor 104.

At step 182, sensor 104 monitors the cathode exhaust stream for hydrogen gas. At step 184, if  
10 sensor 104 measures a hydrogen gas concentration less than threshold concentration TC, the controller 105 decreases the oxidant stoichiometry at step 186. If sensor 104 does not detect a hydrogen gas concentration less than TC, then, at  
15 step 188, controller 105 refers to a look up table to determine the desired oxidant mass flow rate for the instant electrical power output. At step 190, controller 105 determines whether the actual oxidant mass flow rate is more than a  
20 predetermined amount (for example, P%) higher than the desired oxidant mass flow rate. If the actual oxidant mass flow rate is not already greater than P% higher than the desired oxidant mass flow rate, then controller 105 increases the oxidant  
25 stoichiometry at step 192. If, however, the actual oxidant mass flow rate is greater than P% higher than the desired oxidant mass flow rate, then, at step 194, controller 105 generates a warning signal or shuts down the fuel cell. If  
30 controller 105 generates a warning signal, it may also control the fuel cell system to reduce the electrical power output or limit the peak power output. As with the embodiment of FIG. 5, in the method of FIG. 6, the magnitude of the measured  
35 hydrogen gas concentration may be used to determine the appropriate action (that is, a warning signal or shutting down (ceasing operation

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5 of) fuel cell stack 100).

In the logic diagrams of FIGs. 7-9, the methods comprise determining whether the hydrogen gas concentration detected in the cathode exhaust stream is increasing or decreasing, and using this  
10 information to determine what action is appropriate in response to the changing hydrogen gas concentration.

With reference to FIG. 7, the method starts at step 200, by supplying reactants to fuel cell  
15 stack 100 and activating hydrogen sensor 104. At step 202 sensor 104 begins monitoring the cathode exhaust stream for hydrogen gas. Once activated, sensor 104 measures the hydrogen gas concentration in the cathode exhaust stream. Sensor 104  
20 measures the instant hydrogen gas concentration (H) and controller 105 calculates  $dH/dt$  where  $dH$  is the change in H and  $dt$  is the change in time (at constant time intervals). By calculating whether  $dH/dt$  is positive, negative, or zero,  
25 controller 105 determines whether H is increasing, decreasing, or constant, respectively.

Step 204 follows step 202. At step 204, controller 105 determines whether the instant H is higher than a predetermined threshold  
30 concentration (TC). If not, then controller determines that there is no oxidant starvation at the cathode and there is excess oxygen at the cathode. Accordingly, at step 206, controller 105 decreases the oxidant stoichiometry, for example,  
35 by reducing the speed of motor 112 to decrease the oxidant stream mass flow rate supplied to fuel cell stack 100. Oxidant stoichiometry is thus

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5 advantageously controlled to reduce parasitic power consumption.

However, if at step 204, controller determines that the instant  $H$  is greater than  $TC$ , controller 105 advances to step 208 to determine  
10 whether  $dH$  is negative (that is, whether hydrogen concentration is decreasing). If controller 105 determines that  $dH/dt$  is negative, controller 105 preferably returns to step 202 without taking any positive action to counteract  
15 the detection of a hydrogen gas concentration greater than  $TC$ . However, at step 208, if controller 105 determines that  $dH/dt$  is not negative (that is,  $H$  is greater than  $TC$  and the hydrogen concentration is either constant or  
20 increasing), then, controller 105 advances to step 210 and determines whether the oxidant stream mass flow rate is greater than or equal to a desired maximum mass flow rate. If oxidant stream mass flow rate is not greater than or equal to the  
25 desired mass flow rate, then controller 105 proceeds to step 212 and increases the oxidant stoichiometry, preferably by a predetermined increment. Controller 105 then returns to step 202 to determine the effect of the increase in  
30 oxidant stoichiometry and to repeat the method.

At step 210, if controller 105 determines that the oxidant stream mass flow rate is already greater than or equal to a desired maximum mass flow rate, then controller 105 advances to step  
35 214 and generates a warning signal and may eventually shut down fuel cell stack 100 (step 220). In the embodiment shown in FIG. 7,



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5 controller 105 may initiate additional steps 216  
and 218 before proceeding to shut down fuel cell  
stack 100. Since the oxidant stream mass flow  
rate is already greater than or equal to the  
desired maximum, controller 105 proceeds to step  
10 214 to generate a warning signal and then to step  
216 to attempt a corrective action other than  
increasing the oxidant stream mass flow rate. One  
or more leaks within the fuel cell may be the  
cause for detecting an excessive amount of  
15 hydrogen gas in the cathode exhaust stream. For  
example, hydrogen could be leaking from the anode  
fluid passages to the cathode fluid passages, or a  
leak in the oxidant delivery subsystem could  
prevent a sufficient supply of oxygen from being  
20 directed to the cathode.

At step 216, controller 105 reduces the fuel  
pressure in fuel cell stack 100. If one or more  
leaks between the anode and the cathode are the  
cause for detecting hydrogen gas at the cathode,  
25 then reducing fuel pressure at the anode may  
reduce the rate of transfer of fuel from the  
anodes to the cathodes. Fuel pressure may be  
adjusted, for example by adjusting a pressure  
control valve or reducing the speed of a fuel  
30 compressor. Since the fuel stoichiometry may  
initially be greater than one, the reduction in  
fuel pressure may not have an immediate effect on  
electrical power output.

At step 218 controller 105 determines whether  
35 electrical power output is in fact less than  
electrical power demand. If electrical power  
output from fuel cell stack 100 is less than

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5     electrical power demand, then controller 105  
proceeds to shut down fuel cell stack 100. If,  
however, electrical power output continues to  
match electrical power demand, then controller 105  
returns step 202 and the fuel cell system  
10    continues to operate while the method is repeated.  
Meanwhile, the warning signal generated at step  
214 alerts the operator that there is a problem  
that needs to be investigated to determine why H  
is greater than TC.

15             In FIG. 8, the method starts at step 230 and  
advances immediately to step 232 where sensor 104  
begins to monitor the cathode exhaust stream to  
measure hydrogen gas concentration (H), and  
controller 105 calculates  $dH/dt$ . At step 234,  
20    controller 105 determines whether H is greater  
than threshold concentration (TC) or, at step 238,  
whether  $dH/dt$  is negative. The logic of steps  
232, 234, 236, and 238 is substantially the same  
as the logic of corresponding steps shown in FIG.  
25    7 (that is, 202, 204, 206, and 298, respectively).

However, in the method of FIG. 8, if it is  
determined at step 238 that  $dH/dt$  is not negative,  
then controller 105 proceeds to step 240 and  
considers whether the fuel cell voltage is less  
30    than a predetermined voltage  $V_0$ . For example, in  
a preferred embodiment, voltage  $V_0$  is assigned a  
value between zero and about 200 mV. The selected  
value for voltage  $V_0$  is preferably greater than  
zero because localized oxidant starvation may  
35    produce hydrogen even though the overall cell  
voltage is still positive. For example, a  
hydrogen concentration of about 20 ppm may be

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5 measured in the cathode exhaust stream when fuel  
cell stack 100 has an average cell voltage of  
about 100 mV. Accordingly, if controller 105  
determines that there is a combination of a  
positive  $dH/dt$ , and a cell voltage less than  $V_o$ ,  
10 the cause of these two conditions may be oxidant  
starvation. However, if the cell voltage is  
greater than  $V_o$ , this is an indication that cell  
reversal is probably not the cause for detecting  
hydrogen gas in the cathode exhaust.

15 Therefore, if controller 105 determines at  
step 240 that cell voltage is not less than  $V_o$ ,  
controller 105 determines that oxidant starvation  
is not likely the cause for H being greater than  
TC (that is, because oxidant starvation would be  
20 accompanied by a significantly reduced fuel cell  
voltage). More likely, the cause of H being  
greater than TC is one or more fluid leaks between  
the anode and cathode. Accordingly, controller  
105 proceeds to step 246 and reduces the fuel  
25 pressure in fuel cell stack 100 to confirm that  
fluid leaks are indeed the reason for H being  
greater than TC. Steps 248 and 250 are  
essentially the same as steps 218 and 220 in the  
method of FIG. 7.

30 In order to better detect localized oxidant  
starvation conditions in fuel cell stack 100, the  
voltage of the individual fuel cells may be  
monitored. Alternatively, a more simplified cell  
voltage monitoring system may be employed to  
35 measure the cell voltage of selected fuel cells in  
a stack, or the average cell voltage of more than  
one fuel cell in a fuel cell stack. Accordingly,

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5 in the embodiments of FIG. 8 and 9, the measured voltage  $V_o$  may be an individual fuel cell voltage, an average voltage of a plurality of fuel cells, or the average voltage of all the fuel cells in fuel cell stack 100.

10 In the embodiment of FIG. 8, at step 240, if the fuel cell voltage is less than  $V_o$ , controller 105 proceeds to step 242 and checks whether the oxidant stream mass flow rate is already greater than or equal to the desired maximum. If yes,  
15 this is an indication that oxidant starvation is not likely the reason for H being greater than TC, and controller proceeds to step 246. Steps 246, 248 and 250 are similar to corresponding steps 216, 218, and 220 of FIG. 7. If the oxidant  
20 stream mass flow rate is less than the desired maximum, at step 244 controller 105 increases the oxidant stoichiometry, for example, by causing motor 112 to speed up so mechanical device 111 increases the oxidant stream mass flow rate to  
25 fuel cell stack 100.

The method illustrated by FIG. 9 has steps 260, 262, 264, 266, 268, 270, 272, and 274 in common with respective steps 230, 232, 234, 236, 238, 240, 242, and 244 of the method shown in FIG.  
30 8. In FIG. 9, steps 276 and 278 are substituted for steps 246 and 248 in FIG. 8, and additional steps 280 and 284 are added following step 278. If at step 270, controller 105 determines that the fuel cell voltage is not less than  $V_o$ , controller  
35 105 may proceed to step 276 to take further action to confirm that a leak is the likely source of the hydrogen gas in the cathode exhaust stream. At

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5     step 276, the pressure of the oxidant and fuel  
stream are adjusted to regulate the pressure  
differential between the oxidant and fuel stream  
fluid passages. For example, controller 105 may  
cause an increase in the pressure differential  
10    between the oxidant and fuel passages to determine  
whether this has a corresponding effect on H  
detected by sensor 104. If, at step 278, a  
corresponding effect is detected (that is, the  
adjustment of the pressure differential in step  
15    276 influenced the hydrogen gas concentration in  
the cathode exhaust stream), then it is determined  
that a leak is the likely source of the hydrogen  
gas and controller 105 generates a warning signal  
at step 280. Then controller 105 selects whether  
20    to continue operating at a reduce power output  
(step 284) or to shut down the fuel cell (step  
282). If controller 105 selects step 284, it may  
further regulate the oxidant and fuel pressures to  
balance the reactant pressures so that the  
25    pressure differential is approximately zero to  
thereby reduce the amount of hydrogen which is  
transferred from the fuel passages to the oxidant  
passages. The choice between step 282 and step 284  
may be made based on the variance between the  
30    electrical power output and the electrical power  
demand. For example, if the electrical power  
output is more than a predetermined amount less  
than electrical power demand, step 282 is selected  
and fuel cell stack 100 is shut down.  
35           Controller 105 may also proceed to step 276  
from step 272, if the fuel cell voltage is less  
than  $V_0$  and the oxidant mass flow rate is greater

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5 than or equal to a desired maximum.

FIGs. 10 and 11 depict preferred embodiments of a method of controlling the oxidant stoichiometry wherein sensor 104 is periodically activated to detect the presence of hydrogen gas in the cathode exhaust stream. The delay between periodic activation of sensor 104 may vary depending upon several variables. A short delay may be employed for applications where the electrical power output is continually changing, for example where fuel cell stack 100 is supplying electrical power to a drive motor for a vehicle. In such applications, the delay may only be long enough to allow the effects of any corrective actions to be determined. A short delay is desired so that sensor 104 is activated with sufficient frequency to be responsive to changes in electrical power output. Longer delays may be employed by applications such as stationary power plants, which tend to operate to produce a more constant electrical power output.

With reference to FIG. 10, the control logic starts by activating controller 105 at step 290. At step 292, the initial value for the hydrogen gas concentration ( $C_0$ ) is set to zero. At step 294 controller 105 sets counter number "n" to one. At step 296, controller 105 activates sensor 104 to detect the presence of hydrogen gas in a cathode exhaust stream. Sensor 104 emits an output signal that is representative of the hydrogen gas concentration ( $C_n$ ). This output signal is sent to controller 105, which determines at step 298 whether  $C_n$  is greater than the

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5 threshold concentration TC. If  $C_n$  is not greater than TC, then it is assumed that there are no problems with leaks or oxidant starvation. To improve efficiency by reducing parasitic electrical loads, controller 105 proceeds to step  
10 300 and decreases the oxidant stoichiometry by a predetermined amount (for example, a fixed increment or a percentage). Then at step 302, controller 105 increases the value of  $n$  by one before proceeding to step 304. At step 304  
15 controller 105 waits for a predetermined delay period to elapse before returning to step 296 to re-activate sensor 104. Therefore, so long as there is no oxidant starvation, and no leaks or other sources of hydrogen gas in the cathode  
20 exhaust, controller 105 will continue to loop through steps 296, 298, 300, 302 and 304. In this way, the oxidant stoichiometry is reduced to about one or until  $C_n$  is greater than TC. Decreasing oxidant stoichiometry in this manner reduces  
25 parasitic power consumption.

At step 298, when  $C_n$  is greater than TC, controller 105 proceeds to step 306 and compares  $C_n$  to the previously measured hydrogen gas concentration,  $C_{(n-1)}$ . If  $C_n - C_{(n-1)}$  is negative,  
30 this indicates that the hydrogen gas concentration has decreased and controller 105 returns to step 296 via steps 302 and 304. As long as the hydrogen gas concentration is decreasing, controller 105 does not actively take any  
35 corrective action. At step 302, counter number  $n$  is increased by one. Step 304 is the delay step.

However, if at step 306, controller 105

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5 determines that  $C_n - C_{(n-1)}$  is positive, this indicates that the hydrogen gas concentration has increased from the previous measurement. This prompts controller 105 to take corrective action by proceeding to step 308. At step 308,  
10 controller 105 determines from the present oxidant stream mass flow rate whether or not the oxidant stream mass flow rate is greater than or equal to the desired maximum. If not, controller 105 proceeds to step 310 and increases the oxidant  
15 stoichiometry, for example, by causing motor 112 to speed up so mechanical device 111 increases the mass flow rate of the oxidant stream supplied to fuel cell stack 100. After step 310, controller 105 eventually loops back to step 296 after  
20 performing intermediate steps 302 (increasing counter number  $n$  by one) and 304 (the delay step). This corrective action presumes that the cause of the increased concentration of hydrogen gas in the cathode exhaust is oxidant starvation at the  
25 cathode.

However, if oxidant starvation is not the cause for the increasing hydrogen gas concentration in the cathode exhaust, the oxidant stream mass flow rate will soon be increased to  
30 the maximum mass flow rate. Then, at step 308, controller 105 will recognize that oxidant starvation is not the cause of the problem and controller 105 will proceed to step 312.

At step 312, controller 105 reduces the  
35 pressure in the fuel stream by a predetermined amount (for example, a fixed increment or a percentage). If the source of the hydrogen gas



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5 detected in the cathode exhaust is a leak in fuel  
cell stack 100, reducing the pressure in the fuel  
stream may have a corresponding effect on the  
leakage rate. Since the fuel stoichiometry may  
initially be greater than 1.0 (for example, a fuel  
10 stoichiometry of 1.5 or 2.0 is common), decreasing  
the fuel mass flow rate may not initially affect  
the electrical power output. At step 314,  
controller 105 checks whether the electrical power  
output is less than the electrical power demand.  
15 If the electrical power output is not less than  
the electrical power demand, controller 105 loops  
back to step 296 after performing intermediate  
steps 302 and 304. However, if the electrical  
power output is less than electrical power demand,  
20 this indicates that there is a problem with fuel  
cell stack 100 that prevents it from performing at  
this capacity. In this case, controller 105  
proceeds to step 316 where controller 105 either  
generates a warning signal or causes fuel cell  
25 stack 100 to shut down.

With regard to steps 300, 310, and 312 of  
FIG. 10, the respective oxidant stoichiometry or  
fuel pressure may be increased and decreased by a  
predetermined fixed percentage or a fixed  
30 increment. For example, the fixed percentage  
change in oxidant stoichiometry or fuel pressure  
may be 1 or 2%.

With reference to FIG. 11, steps 320, 322,  
324, 326, 328, 332, 334, 336, 340, 342, 344, and  
35 346 are substantially the same as steps 290, 292,  
294, 296, 298, 302, 304, 306, 308, 312, 314 and  
316 of FIG. 10, respectively. However, in the

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5 method of FIG. 11, controller 105 attempts to maintain an oxidant stoichiometry that is a desired amount above 1.0 (that is,  $1.0 + Y$ ). For example Y may be, for example, 0.05, 0.10, 0.20, ... or even about 0.50 (that is, about 50%).

10 Preferably Y represents an increase of less than 50% to avoid excessive parasitic power consumption. In this way, a small surplus oxidant buffer is provided to reduce the occurrence of oxidant starvation conditions that might produce

15 hydrogen gas in the cathode exhaust. The oxidant stoichiometry is still preferably much less than the oxidant stoichiometries used in conventionally operated fuel cells so there is still a substantial reduction in the parasitic electrical

20 load caused by the operation of oxidant stream mechanical device 111.

In the embodiment of FIG. 11, after step 328, if controller 105 determines that the hydrogen gas concentration ( $C_H$ ) is less than threshold

25 concentration TC, then controller loops back to step 326 via steps 330, 332 (increasing counter number n by one), and 334 (the delay step). At step 330 controller 105 decreases the oxidant stoichiometry by a predetermined increment (X),

30 where X may be, for example, about 0.1 or about 0.2. Accordingly, if, for example, X is 0.1 and oxidant stoichiometry is 1.4, at step 330 controller 105 would adjust oxidant stream mass flow rate to decrease oxidant stoichiometry to

35 1.3. Thus, while there is an excess of oxidant at the cathode, oxidant stream mass flow rate is reduced through the loop comprising steps 326,

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5     328, 330, 332 and 334 until controller 105 determines at step 328 that  $C_n$  is greater than TC, whereupon controller 105 proceeds to step 336.

Step 336 of FIG. 11 performs substantially the same function as step 306 of FIG. 10. That is, if the hydrogen gas concentration is decreasing (that is,  $C_n - C_{(n-1)}$  is negative), then controller returns to step 326 via steps 332 and 334. Controller 105 continues to periodically monitor  $C_n$  without taking any action to actively increase oxidant stoichiometry. However, if controller 105 determines at step 328 that  $C_n > TC$ , and at step 336, that the hydrogen gas concentration is constant or increasing (that is,  $C_n - C_{(n-1)}$  is not negative), the controller 105 proceeds to step 338.

At step 338, if controller 105 determines that the previous measurement of the hydrogen gas concentration was less than TC, controller 105 increases the oxidant stream mass flow rate by  $(X + Y)$  at step 348. For example, when TC corresponds to an oxidant stoichiometry of about one, in the method of FIG. 11, at step 348 oxidant stoichiometry is controlled so that it is approximately  $1.0 + Y$ . That is, in the previous loop, hydrogen concentration  $C_{(n-1)}$  was less than TC, but decreasing oxidant stoichiometry by X caused the hydrogen concentration in the next loop (that is, the present loop) to be higher than TC.

Accordingly, in the previous loop,  $C_{(n-1)}$  was close in value to TC, and since in this example, a measured hydrogen concentration of about TC corresponds to an oxidant stoichiometry of about

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5 one, increasing oxidant stoichiometry by  $(X + Y)$ , results in an oxidant stoichiometry of about  $1.0 + Y$ .

If at step 338, controller 105 determines that the previously measured hydrogen gas  
10 concentration was greater than TC, controller 105 proceeds to step 340 to determine whether the oxidant stream mass flow rate is already greater than or equal to a desired maximum. If not, controller 105 proceeds to step 350 and increases  
15 the oxidant stoichiometry by Z. The value of Z is preferably greater than  $(X + Y)$  so that when  $C_n$  is higher than TC for more than one loop, the oxidant stoichiometry is increased more rapidly.

However, if at step 340 controller 105  
20 determines that oxidant stream mass flow rate is already greater than or equal to a desired maximum, controller 105 proceeds to step 342. Steps 342, 344 and 346 are substantially the same as respective steps 312, 314 and 316 in FIG. 10.

25 FIG. 12 depicts another preferred embodiment of a method of controlling the supply of oxidant to a fuel cell. In the method of FIG. 12 the preferred oxidant stream supply mass flow rate for a predetermined oxidant stoichiometry is  
30 calibrated for a range of specific electrical power outputs. During a calibration procedure, controller 105 determines the desired oxidant stream mass flow rates (for a particular oxidant stream composition) for selected electrical power  
35 outputs and stores the desired mass flow rates in a look-up table. When this method is employed, the electrical power demand determines the oxidant

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5 stream mass flow rate. That is, a controller monitors the electrical power demand and sets the oxidant mass flow rate with reference to a look-up table, which indicates the desired oxidant stream mass flow rate for selected electrical power demands. In this way, the oxidant stoichiometry is controlled to reduce the amount of excess oxidant supplied to fuel cell stack 100, thereby reducing parasitic electrical power consumption.

10 FIG. 12 depicts a calibration procedure for determining the oxidant stream mass flow rate for different selected electrical power outputs. When fuel cell stack 100 is actually operating, if the electrical power output is between selected loads in the look-up table, the desired oxidant stream mass flow rate may be determined by interpolating between selected electrical loads to determine the desired oxidant stream mass flow rate.

15 In an alternative embodiment, the calibration procedure may be used to calibrate the oxidant supply system directly. For example, in a system that employs an oxidant compressor, the system is calibrated to control the speed of the compressor in response to selected electrical power demands. In this way, oxidant stream mass flow rate need not be measured and with each calibration, the calibration process will automatically compensate for any degradation in compressor performance over its operational lifetime.

20 The calibration procedure depicted in FIG. 12 may be executed periodically when fuel cell stack 100 is being serviced for regular maintenance. The procedure begins at step 360, by activating

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5 controller 105. In this embodiment, because calibration is typically done during maintenance periods, controller 105 and sensor 104 may be detachable from the fuel cell system. In this way, the same equipment may be used to calibrate a plurality of fuel cell stacks. A coupling may be provided so that a sensing element may be inserted into the fuel cell so that the sensing element is exposed to the cathode exhaust stream.

10 At step 362 an electrical power output is selected and fuel cell stack 100 is operated to produce that electrical power output. The selected electrical power output may be any electrical power output within the operating range of fuel cell stack 100. A plurality of electrical power outputs are typically selected during the calibration procedure so it is convenient to start with an electrical power output at the low end of the range; progressively higher electrical power outputs may be subsequently selected to complete the calibration procedure.

25 At step 364, controller 105 accesses a look-up table to determine the previously calibrated oxidant stream mass flow rate for the selected electrical power output. Controller 105 then sets the oxidant stream mass flow rate so that it is initially 1% higher than the previously calibrated oxidant stream mass flow rate for the selected electrical power output. It is preferable to calibrate the oxidant stream mass flow rate by starting with a surplus oxidant stream mass flow rate rather than a shortage of oxidant, since this precaution avoids initiating the calibration

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5 procedure in an oxidant starvation mode.

At step 366 sensor 104 is activated to detect the presence of hydrogen gas in the cathode exhaust stream. If fuel cell stack 100 is initially supplied with a surplus of oxidant, at  
10 step 368, the hydrogen gas concentration  $C$  is expected to be less than a threshold concentration  $TC$ . If controller 105 determines that  $C$  is not greater than  $TC$ , controller 105 continues to decrease the oxidant stream mass flow rate by  
15 looping back to step 366 via step 370. With each loop through step 370, controller 105 decreases the oxidant stream mass flow rate by increment  $A$ . For example, the value of increment  $A$  may correspond to stoichiometry reductions, of say  
20 0.05 or 0.1 so that oxidant stoichiometry is reduced by that amount each time step 370 is performed. Because the selected load is constant during the calibration procedure, changes in the oxidant stream mass flow rate result in  
25 corresponding changes in the oxidant stoichiometry. The accuracy of the calibration procedure may be increased by decreasing the value of  $A$  so that more calibration loops are performed using smaller incremental reductions in the  
30 oxidant stream mass flow rate.

When the oxidant stream mass flow rate is finally reduced so that hydrogen gas concentration  $C$  is greater than  $TC$ , controller 105 proceeds to step 372 and increases the oxidant stream mass  
35 flow rate by increment  $B$ . Next, at step 374, controller 105 resets the look-up table value so that the desired oxidant stream mass flow rate in

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5 the look-up table matches the current mass flow rate for the selected electrical power output. Finally, controller 105 may choose to stop the calibration procedure at step 378, or to select a different electrical power output for oxidant  
10 stream mass flow rate calibration at step 376. If step 376 is chosen, a different electrical power output is selected and controller 105 returns to step 364 where the calibration procedure begins again for the newly selected electrical power  
15 output.

The value of A and B may be the same or B may be higher than A. When B is higher than A, the look up table values will be calibrated so that there will be a surplus of oxidant supplied to the  
20 cathode. The greater the difference between the values for B and A, the greater will be the surplus. A surplus supply of oxidant helps to reduce the likelihood of causing oxidant starvation conditions that might produce hydrogen  
25 gas in the oxidant stream. When the power output is expected to be dynamic, a higher oxidant stoichiometry may be preferred to prevent oxidant starvation during transitional periods when electrical power output is changing. The value of  
30 B is preferably selected so that the oxidant stoichiometry is generally less than two and preferably between about one and about 1.5.

While particular elements, embodiments and applications of the present invention have been  
35 shown and described, it will be understood, of course, that the invention is not limited thereto since modifications may be made by those skilled



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- 5 in the art without departing from the spirit and scope of the present disclosure, particularly in light of the foregoing teachings.

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## 5 WHAT IS CLAIMED IS:

1. A method of operating a fuel cell system, said system comprising a fuel cell power... generating subsystem having at least one fuel  
10 cell, and an oxidant delivery subsystem, comprising a mechanical device for supplying an oxidant stream to a cathode of said fuel cell, wherein said method comprises controlling said mechanical device to reduce parasitic power  
15 consumption by reducing oxidant stoichiometry until  $dV/d(\text{oxidant stoichiometry})$  is greater than a predetermined value.
- 20 2. The method of claim 1 wherein said fuel cell is a solid polymer electrolyte fuel cell.
3. The method of claim 1 wherein said predetermined value of  $dV/d(\text{oxidant stoichiometry})$   
25 is greater than or equal to 0.02 volt.
4. The method of claim 1 wherein said predetermined value or  $dV/d(\text{oxidant stoichiometry})$   
30 is between about 0.3 volt and about 7.0 volts.
5. The method of claim 1 wherein said predetermined value of  $dV/d(\text{oxidant stoichiometry})$   
is determined when cell voltage decreases below a threshold voltage.  
35
6. The method of claim 1 wherein said predetermined value of  $dV/d(\text{oxidant stoichiometry})$

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5 is determined when oxidant starvation is occurring at the cathode electrochemically active area.

7. The method of claim 5 wherein the determination that  $dV/d(\text{oxidant stoichiometry})$  is greater than said predetermined value is made by  
10 detecting a threshold concentration of hydrogen in the cathode exhaust stream.

8. The method of claim 1 wherein said  
15 predetermined value for  $dV/d(\text{oxidant stoichiometry})$  is determined when said oxidant stoichiometry is less than a threshold value that is between about 1.0 and about 2.0.

9. The method of claim 8 further  
20 comprising measuring oxygen concentration within said cathode exhaust stream to calculate oxidant stoichiometry to determine when said oxidant stoichiometry is less than said threshold oxidant  
25 stoichiometry.

10. The method of claim 1 wherein said predetermined value for  $dV/d(\text{oxidant stoichiometry})$  is determined when the value of  
30 said cell voltage is less than a threshold cell voltage and cell voltage is monitored to determine when to cease reducing oxidant stoichiometry.

11. The method of claim 10 further  
35 comprising controlling said oxidant delivery subsystem to maintain voltage output within a predetermined voltage range which corresponds to

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5 an oxidant stoichiometry range between about 1.0 and about 2.0, wherein said threshold cell voltage corresponds to the cell voltage at the lower limit of said predetermined voltage range.

10 12. The method of claim 1 wherein said oxidant stream is a dilute oxidant stream.

13. The method of claim 12 wherein said oxidant stream is air.

15 14. The method of claim 8 further comprising controlling said mechanical device to maintain oxidant stoichiometry at about 1.0 during steady state operating conditions.

20 15. The method of claim 1 wherein said mechanical device is selected from the group consisting of a compressor, a fan, a pump, and a blower, and wherein oxidant stoichiometry is  
25 reduced by reducing the speed of said mechanical device.

16. The method of claim 9 wherein the method of determining oxidant stoichiometry  
30 further comprises monitoring oxygen concentration in an oxidant supply stream that is directed to said cathode.

17. The method of claim 9 further comprising  
35 monitoring electrical current output from said fuel cell power generating subsystem.

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5           18. A method of operating a fuel cell,  
wherein said fuel cell has a cathode supplied with  
an oxidant stream and an anode supplied with a  
fuel stream, said method comprising:

10           (a) monitoring a cathode exhaust stream  
downstream of said cathode to detect hydrogen gas  
concentration; and

          (b) decreasing oxidant stoichiometry when  
said hydrogen gas concentration is less  
than a first threshold concentration.

15           19. The method of claim 18 wherein said fuel  
cell is one of a plurality of fuel cells arranged  
in a fuel cell stack and said cathode exhaust  
stream is monitored downstream of a plurality of  
20 cathodes associated with said plurality of fuel  
cells.

          20. The method of claim 18 further  
comprising increasing said oxidant stoichiometry  
25 when said hydrogen gas concentration is greater  
than a second threshold concentration.

          21. The method of claim 20 wherein said  
first threshold concentration is the lower  
30 detection limit of a hydrogen sensor used to  
monitor said cathode exhaust stream.

          22. The method of claim 20 wherein said  
second threshold concentration is about 20 ppm of  
35 hydrogen.

          23. The method of claim 20 wherein said

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5     second threshold concentration is greater than  
said first threshold concentration.

24.   The method of claim 20 wherein said  
oxidant stoichiometry is adjusted by adjusting the  
10    oxidant concentration in said oxidant stream  
supplied to said cathode.

25.   The method of claim 20 wherein said  
oxidant stoichiometry is adjusted by adjusting the  
15    electrical power output of said fuel cell.

26.   The method of claim 20 wherein said  
oxidant stoichiometry is adjusted by adjusting the  
mass flow rate of said oxidant stream supplied to  
20    said cathode.

27.   The method of claim 26 wherein said  
oxidant stream mass flow rate is adjusted by  
adjusting the speed of a mechanical device which  
25    supplies said oxidant stream to said cathode.

28.   The method of claim 26 wherein said  
oxidant stream mass flow rate is adjusted by a  
fixed amount or by a fixed percentage of the  
30    instantaneous oxidant stream mass flow rate.

29.   The method of claim 26 wherein said  
oxidant stoichiometry is adjusted by adjusting  
said oxidant stream mass flow rate by an amount  
35    that is dependent upon the magnitude of the  
detected hydrogen gas concentration.

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5           30. The method of claim 18 further  
comprising steps for reducing said hydrogen gas  
concentration within said cathode exhaust stream  
when said hydrogen gas concentration is greater  
than a second threshold concentration, wherein  
10 said steps comprise comparing said oxidant stream  
mass flow rate to a maximum desired mass flow  
rate, and

(a) if said oxidant stream mass flow rate is  
less than said maximum desired mass flow  
15 rate, increasing said oxidant mass flow  
rate; and

(b) if said oxidant mass flow rate is  
greater than or equal to said maximum  
desired mass flow rate, ceasing  
20 operation of said fuel cell if said  
hydrogen gas concentration is greater  
than a third concentration threshold  
which is greater than said first and  
second concentration thresholds; and  
25 generating a warning signal and  
continuing to operate said fuel cell if said  
hydrogen gas concentration is less than said third  
concentration threshold.

30           31. The method of claim 20 wherein said  
method further comprises taking no steps to change  
said oxidant stoichiometry when said hydrogen gas  
concentration is between said first and second  
threshold concentrations.

35

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5           32. The method of claim 26 further  
comprising, after increasing said oxidant mass  
flow rate, comparing said oxidant mass flow rate  
to a desired oxidant mass flow rate for the  
instantaneous fuel cell electrical power output,  
10       and generating a warning signal or ceasing  
operation of said fuel cell if said oxidant mass  
flow rate is more than a predetermined amount  
greater than said desired oxidant mass flow rate.

15           33. The method of claim 30 wherein said  
desired oxidant mass flow rate is determined from  
a look-up table.

2           34. The method of claim 18 wherein said  
20       monitoring comprises continuously monitoring said  
cathode exhaust stream for said hydrogen gas  
concentration and determining whether said  
hydrogen gas concentration is increasing or  
decreasing, and when said hydrogen gas  
25       concentration is greater than a second threshold  
concentration, said method further comprises:  
              maintaining a substantially constant  
oxidant stoichiometry when said hydrogen  
concentration is decreasing; and  
30       increasing said oxidant stoichiometry  
when said hydrogen concentration is  
increasing.



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5

35. The method of claim 34 further comprising:

generating a warning signal if said hydrogen gas concentration is greater than said first threshold concentration, said hydrogen gas concentration within said cathode exhaust stream is increasing, and said oxidant stream is flowing at a maximum desired mass flow rate.

15

36. The method of claim 35 further comprising controlling said fuel stream to decrease fuel stream pressure when said warning signal is generated.

20

37. The method of claim 36 further comprising monitoring electrical power output of said fuel cell, and continuing to operate said fuel cell if said electrical power output is not less than electrical power demand, and ceasing operation of said fuel cell if said electrical power output is a predetermined amount less than said electrical power demand.

25  
30

38. The method of claim 36 further comprising checking electrical power output and, continuing to operate said fuel cell if said electrical power output is not less than electrical power demand, and generating a warning signal if said

35

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5           electrical power output is less than said  
          electrical power demand and then selecting  
          between operating at a reduced electrical  
          power output and ceasing operation of said  
          fuel cell.

10

39. The method of claim 18 wherein said  
monitoring comprises continuously monitoring said  
cathode exhaust stream for said hydrogen gas  
concentration and determining whether said  
15   hydrogen gas concentration is increasing or  
     decreasing, and when said hydrogen gas  
     concentration is greater than a second threshold  
     concentration, said method further comprises:

          maintaining a constant oxidant  
20   stoichiometry when said hydrogen  
     concentration is decreasing; and  
          measuring fuel cell voltage and  
     comparing said fuel cell voltage to a voltage  
     threshold value, and

25           if said fuel cell voltage exceeds  
          said voltage threshold value and said  
          hydrogen gas concentration is  
          increasing, decreasing the pressure of  
          said fuel stream;

30           if said fuel cell voltage is less  
          than said voltage threshold value, said  
          hydrogen gas concentration is  
          increasing, and oxidant mass flow rate  
          is less than a desired maximum, then  
35   increasing said oxidant stoichiometry;  
     and

          if said fuel cell voltage is less

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5           than said voltage threshold value, said  
hydrogen gas concentration is  
increasing, and oxidant mass flow rate  
is greater than or equal to a desired  
10           maximum, then decreasing the pressure of  
said fuel stream.

40. The method of claim 39 further  
comprising regulating fluid pressure of said  
oxidant and fuel streams to increase a pressure  
15       differential between said oxidant and fuel  
streams.

41. The method of claim 39 further  
comprising regulating fluid pressure of said  
20       oxidant and fuel streams to reduce a pressure  
differential between said oxidant and fuel  
streams.

42. The method of claim 39 wherein said  
25       voltage threshold value is about 100 millivolts.

43. The method of claim 39 further  
comprising ceasing operation of said fuel cell  
when electrical power output is less than  
30       electrical power demand.

44. The method of claim 18 wherein said  
monitoring is performed periodically.

45. The method of claim 26 wherein said  
35       oxidant stream mass flow rate is reduced until  
said second predetermined threshold concentration

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5 of said hydrogen gas is detected and then  
increasing said oxidant mass flow rate by a  
predetermined percentage so that said oxidant  
stoichiometry is a predetermined percentage higher  
than about one.

10

46. The method of claim 45 wherein said  
predetermined percentage is less than 50%.

15

47. A method of calibrating an oxidant  
delivery subsystem for a fuel cell, said method  
comprising:

- (a) operating said fuel cell at a particular  
electrical power output;
- (b) supplying an oxidant stream to a cathode  
20 of said fuel cell;
- (c) adjusting the operating speed of a  
mechanical oxidant delivery device;
- (d) measuring an operational characteristic  
that corresponds to  $dV/d(\text{oxidant stoichiometry})$ ; and
- 25 (e) recording as the desired operating speed  
for said particular electrical power  
output, said operating speed when said  
 $dV/d(\text{oxidant stoichiometry})$  is equal to  
30 a predetermined value.

35

48. The method of claim 47 wherein said  
method is repeated for a plurality of electrical  
power outputs.

49. The method of claim 47 wherein said  
operational characteristic is cell voltage.

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5           50. The method of claim 47 wherein said  
operational characteristic is oxidant  
stoichiometry.

          51. A fuel cell system comprising:  
10           a fuel cell comprising an anode, a  
cathode and a cathode exhaust passage fluidly  
connected to said cathode;  
          an oxidant supply for supplying an  
oxidant stream to said fuel cell cathode;  
15           a sensor associated with said fuel cell  
for monitoring an operational characteristic  
which correlates to  $dV/d(\text{oxidant stoichiometry})$ ; and  
          a controller in communication with said  
20           sensor for receiving and processing a signal  
from said sensor to determine whether  
 $dV/d(\text{oxidant stoichiometry})$  is greater than a  
predetermined value and controlling said  
oxidant supply, to decrease oxidant  
25           stoichiometry if  $dV/d(\text{oxidant stoichiometry})$   
is less than said predetermined value.

          52. The fuel cell system of claim 51 wherein  
said fuel cell is a solid polymer fuel cell.

30           53. The fuel cell system of claim 52 wherein  
said sensor monitors the voltage output of said  
fuel cell.

35           54. The fuel cell system of claim 52 wherein  
said sensor measures the oxidant concentration in  
said cathode exhaust passage.

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5

55. The fuel cell system of claim 52 wherein said sensor measures the concentration of hydrogen in said cathode exhaust passage.

10

56. The fuel cell system of claim 52 wherein said controller further controls said oxidant supply to increase oxidant stoichiometry if said controller determines that  $dV/d(\text{oxidant stoichiometry})$  is greater than said predetermined value.

15

57. The fuel cell system of claim 56 wherein said oxidant supply comprises a mechanical device selected from the group consisting of compressors, fans, pumps, and rotary piston blowers, for supplying said oxidant stream to said cathode and said controller adjusts oxidant stoichiometry by adjusting the speed of said mechanical device to control oxidant stream mass flow rate.

25

58. The fuel cell system of claim 56 wherein said fuel cell is one of a plurality of fuel cells arranged in a stack between two end plates and said sensor is located in a portion of said cathode exhaust passage disposed between outside end surfaces of said end plates.

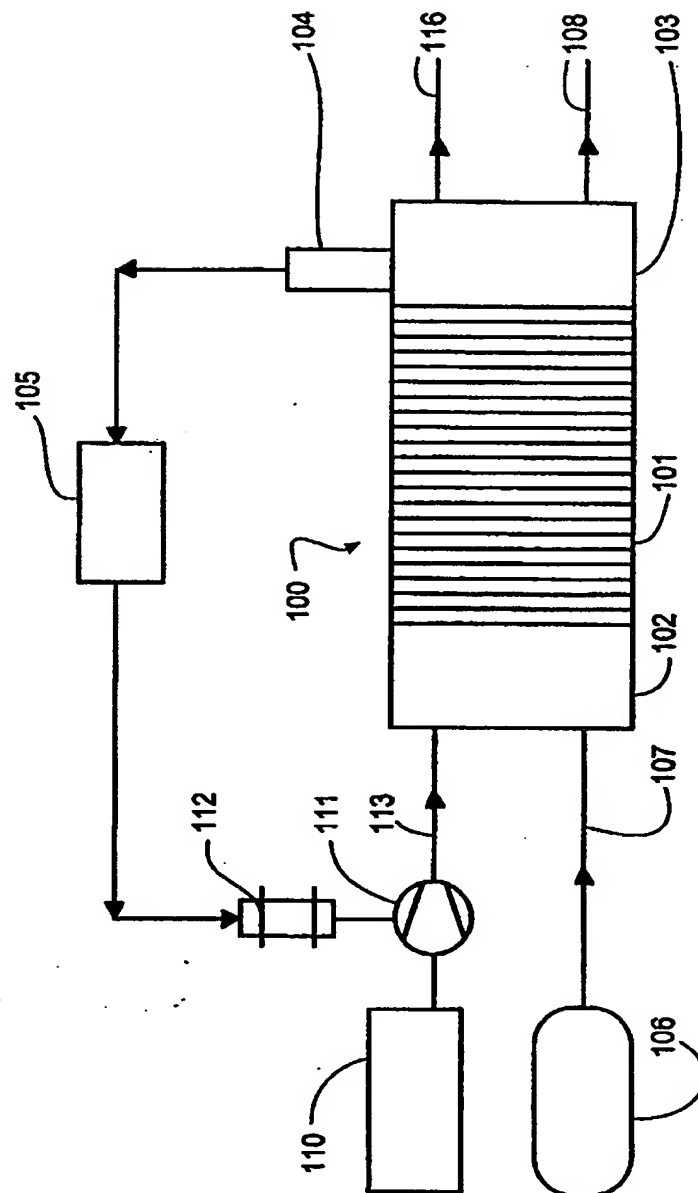
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59. The fuel cell system of claim 55 wherein said cathode exhaust passage comprises an internal cathode exhaust manifold within said fuel cell and said sensor comprises a sensing element located in said internal cathode exhaust passage.

35

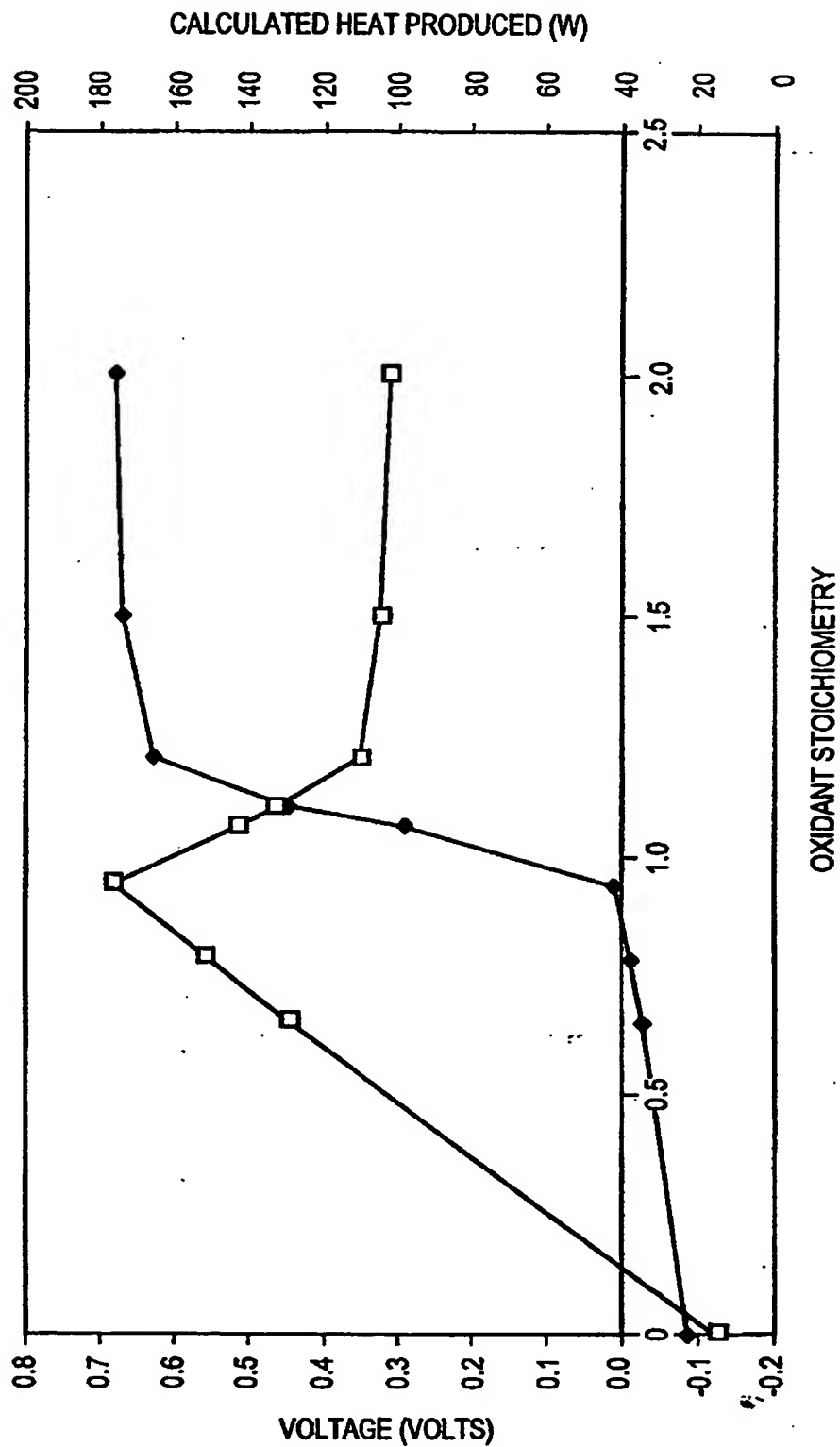
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FIG. 1



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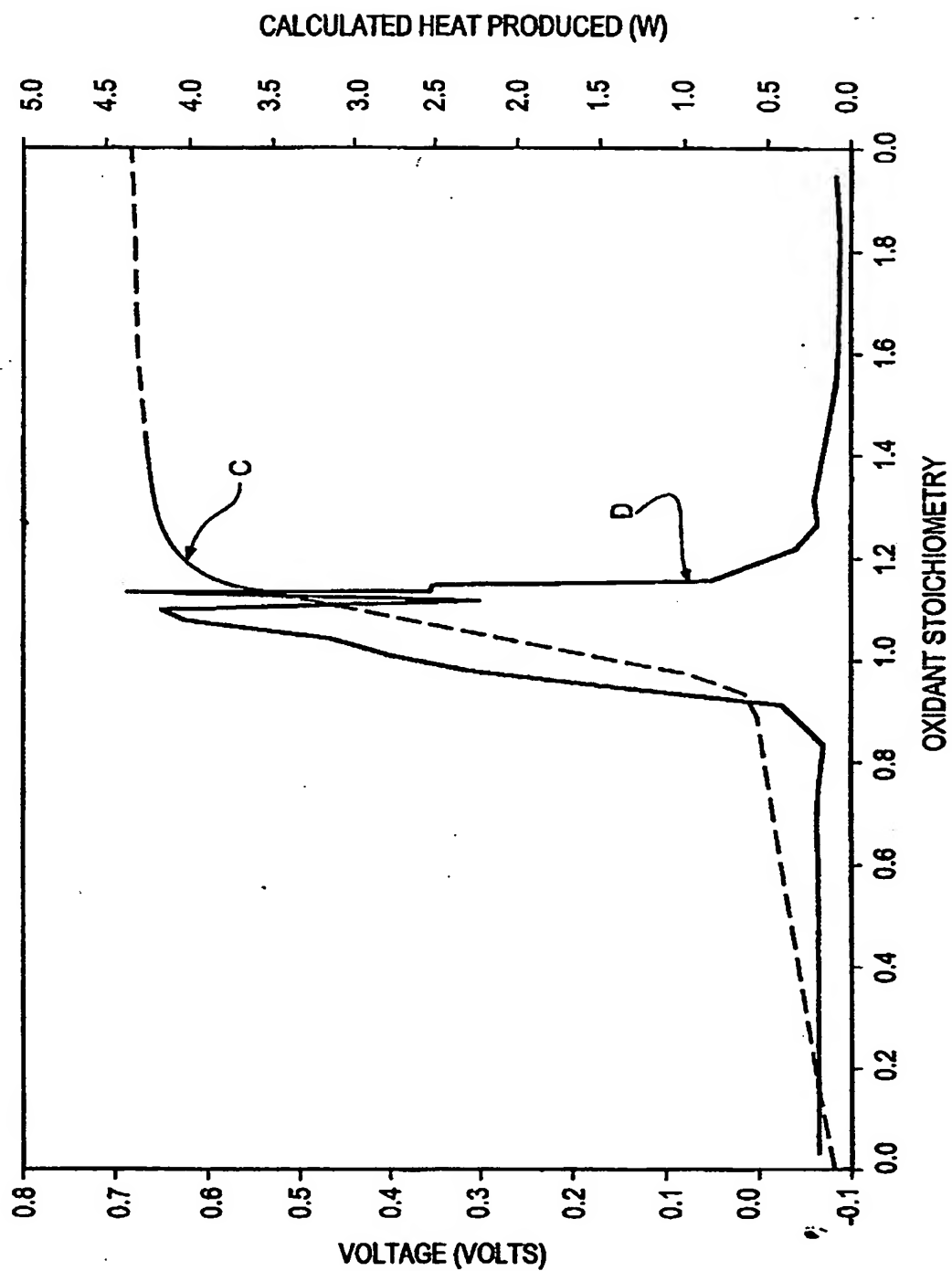
FIG. 2A





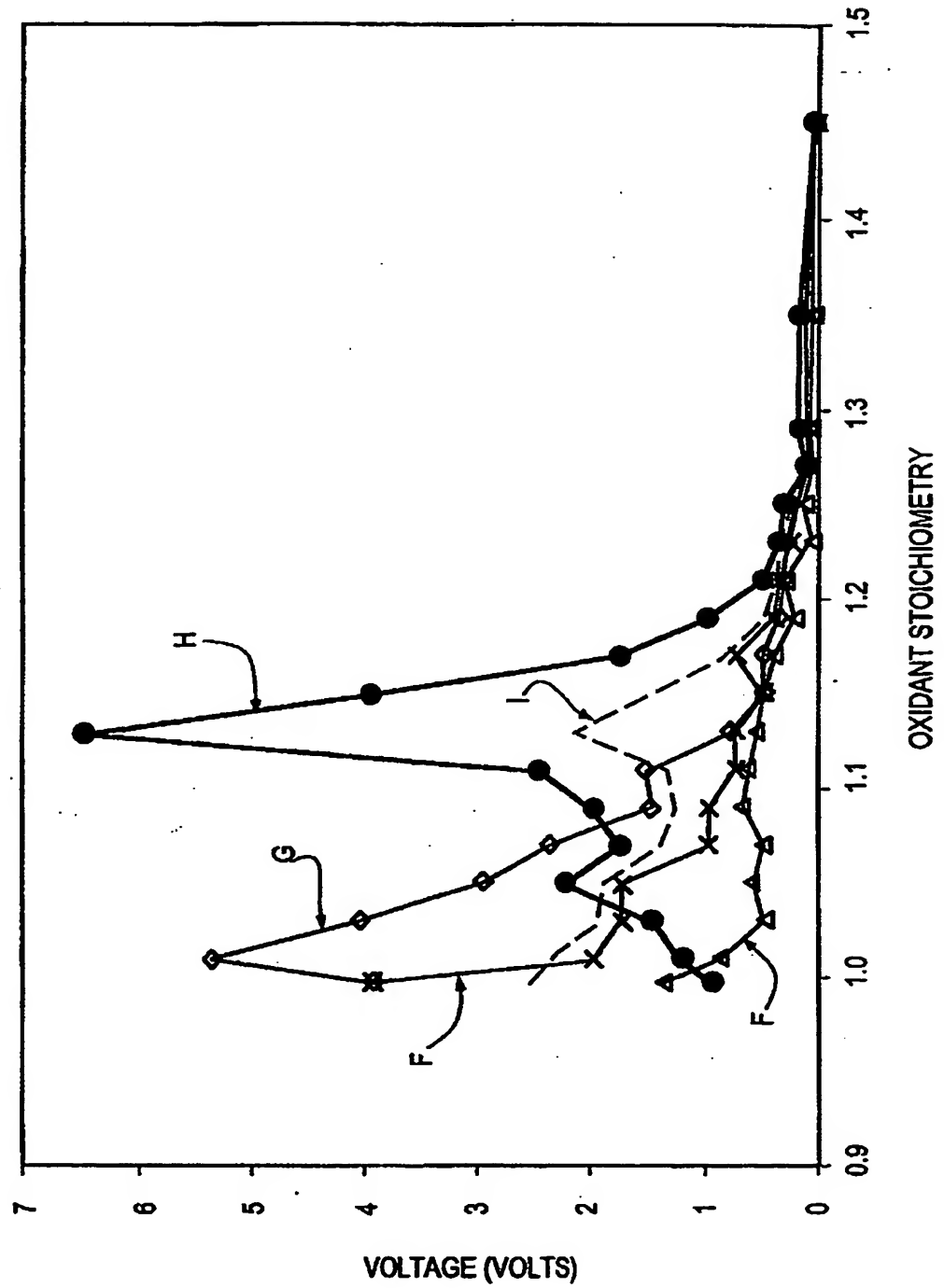
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FIG. 2B



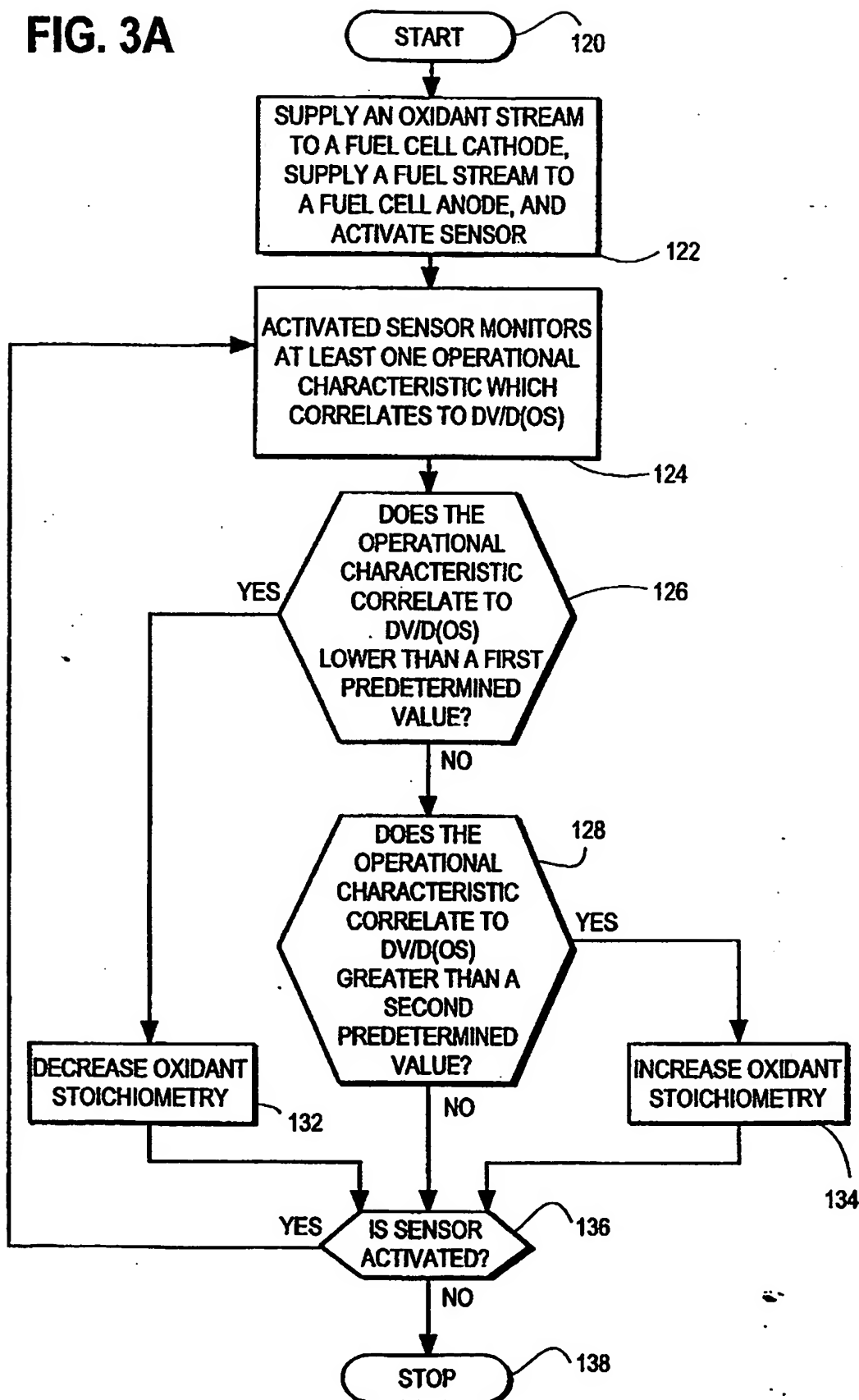
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FIG. 2C



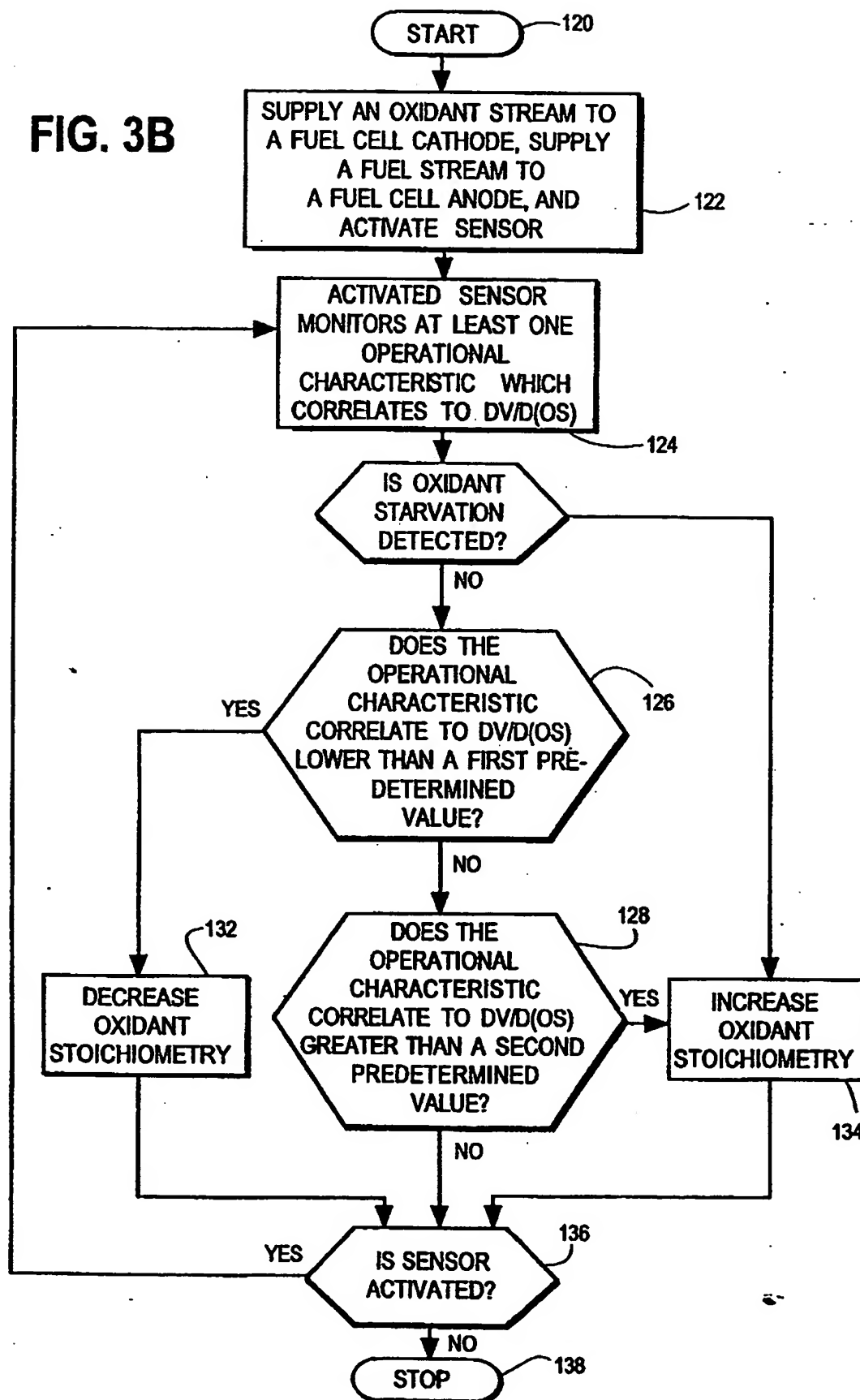
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FIG. 3A



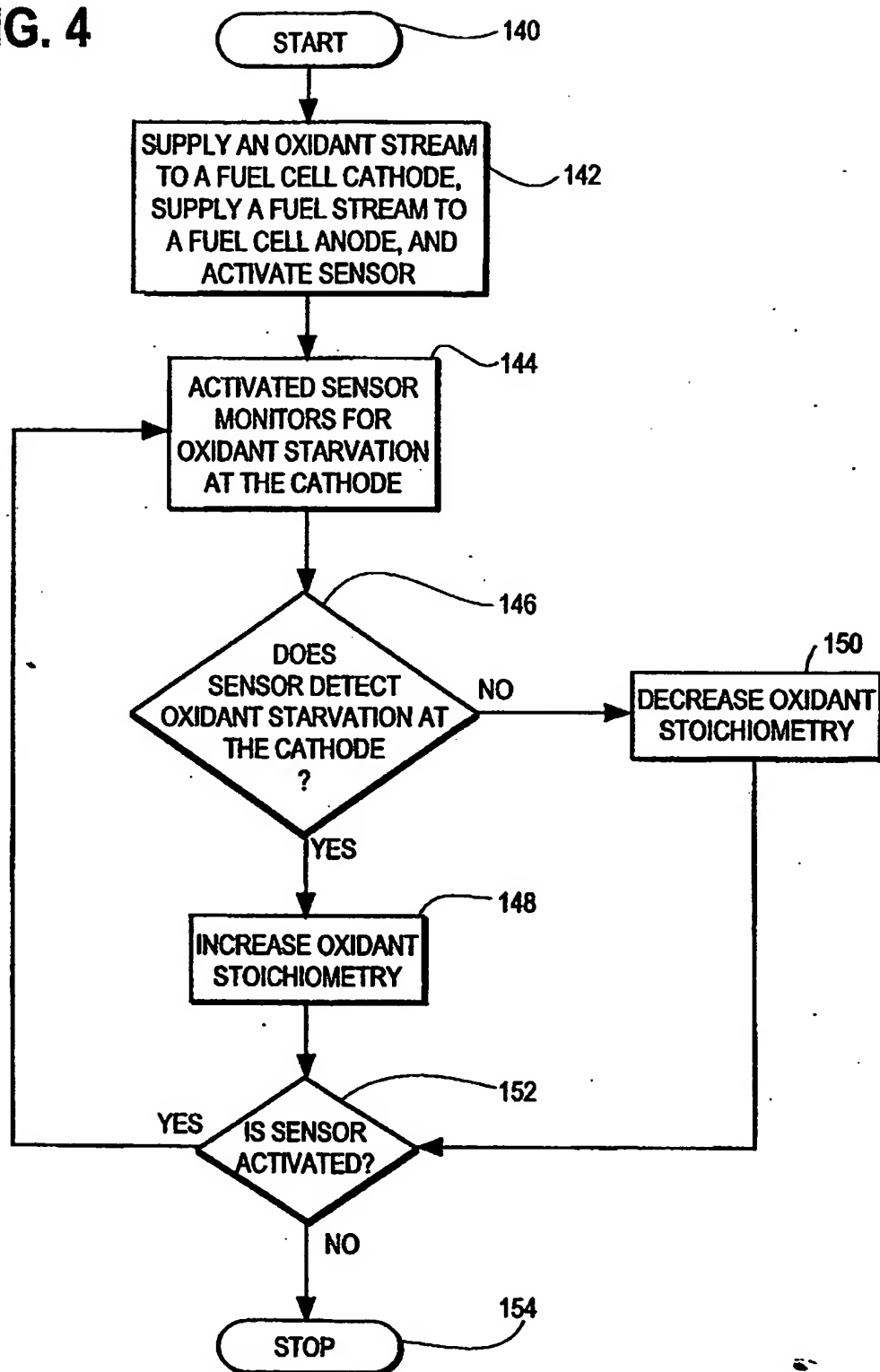
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FIG. 3B



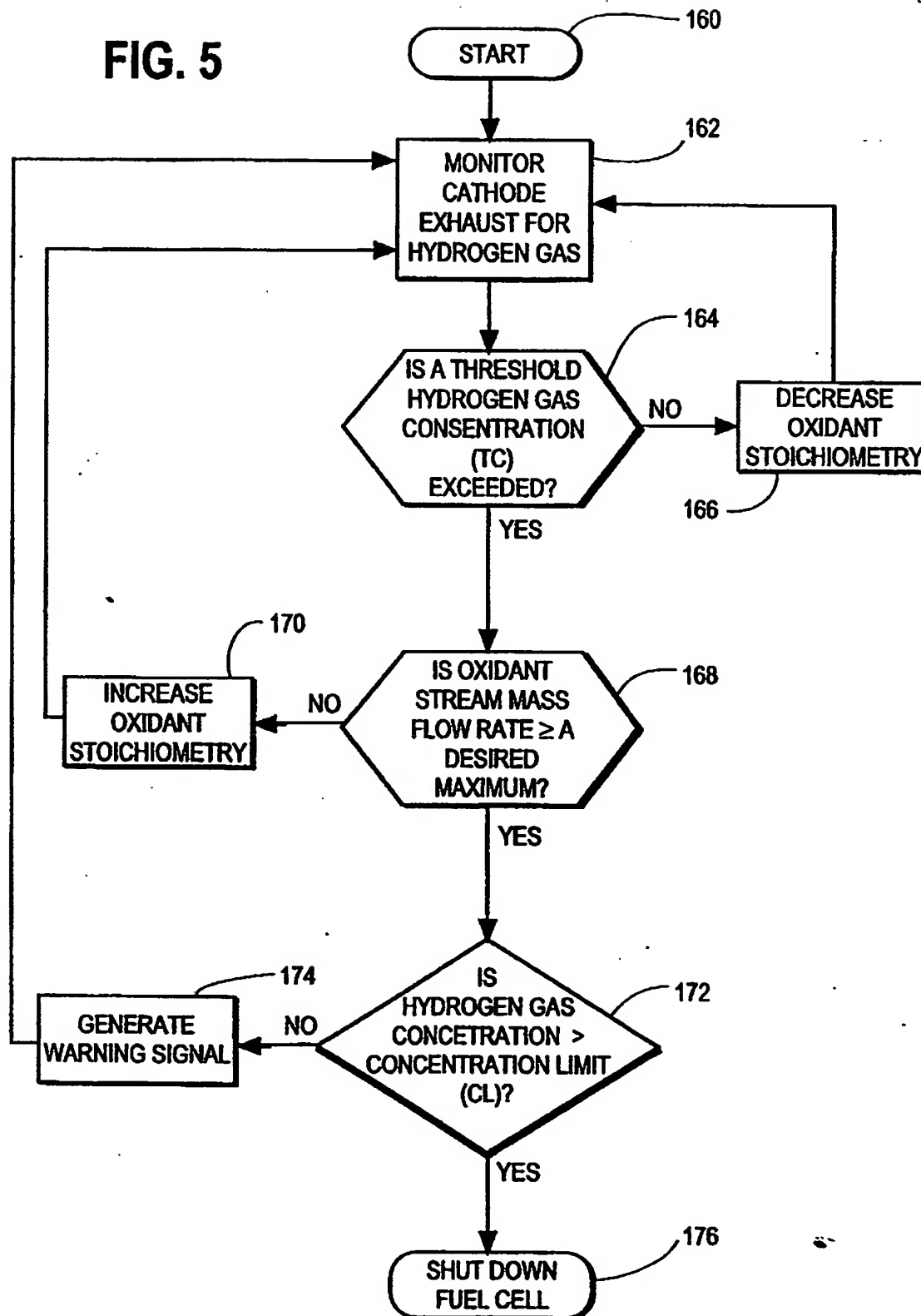
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FIG. 4



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FIG. 5



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FIG. 6

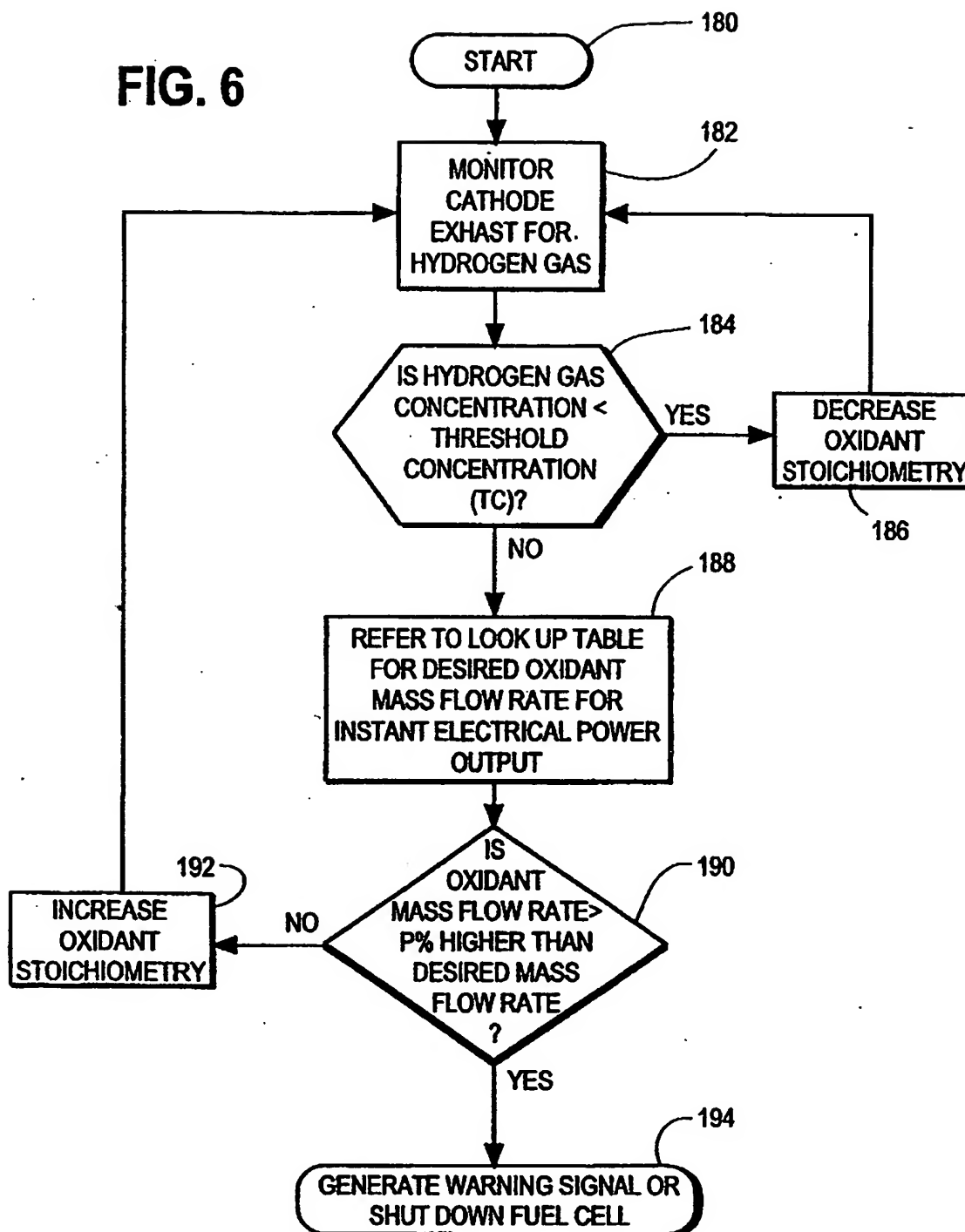
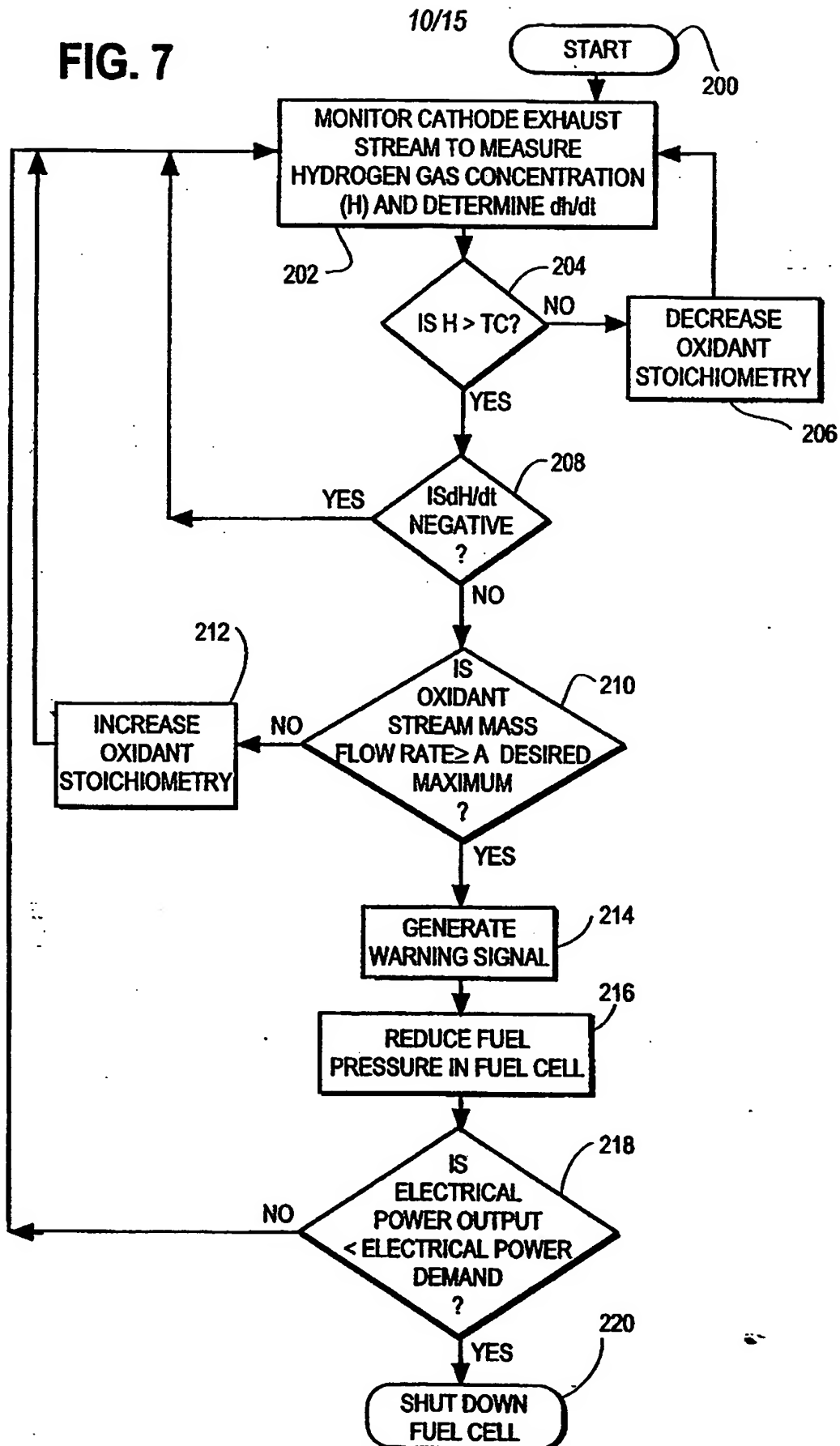


FIG. 7





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FIG. 8

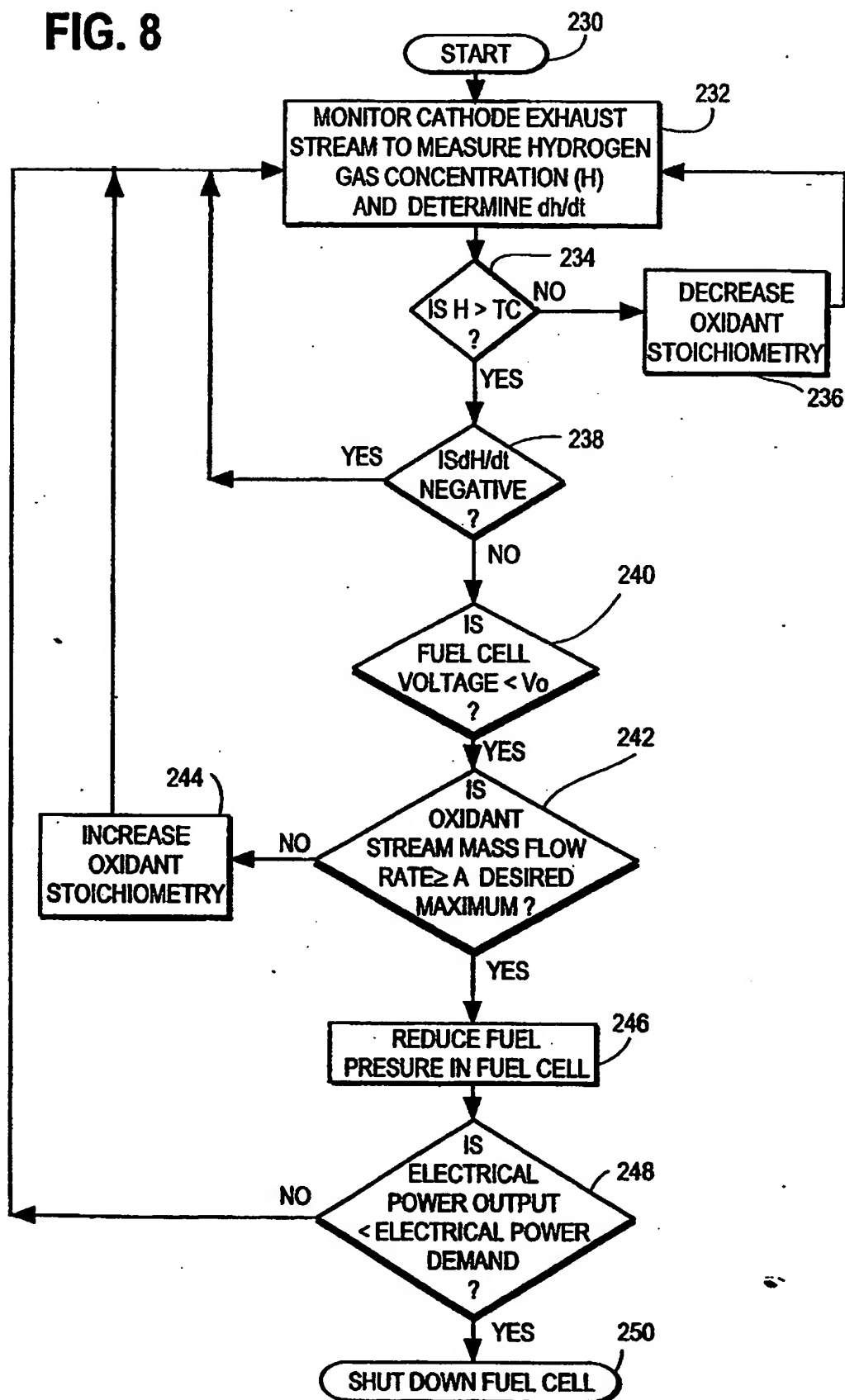
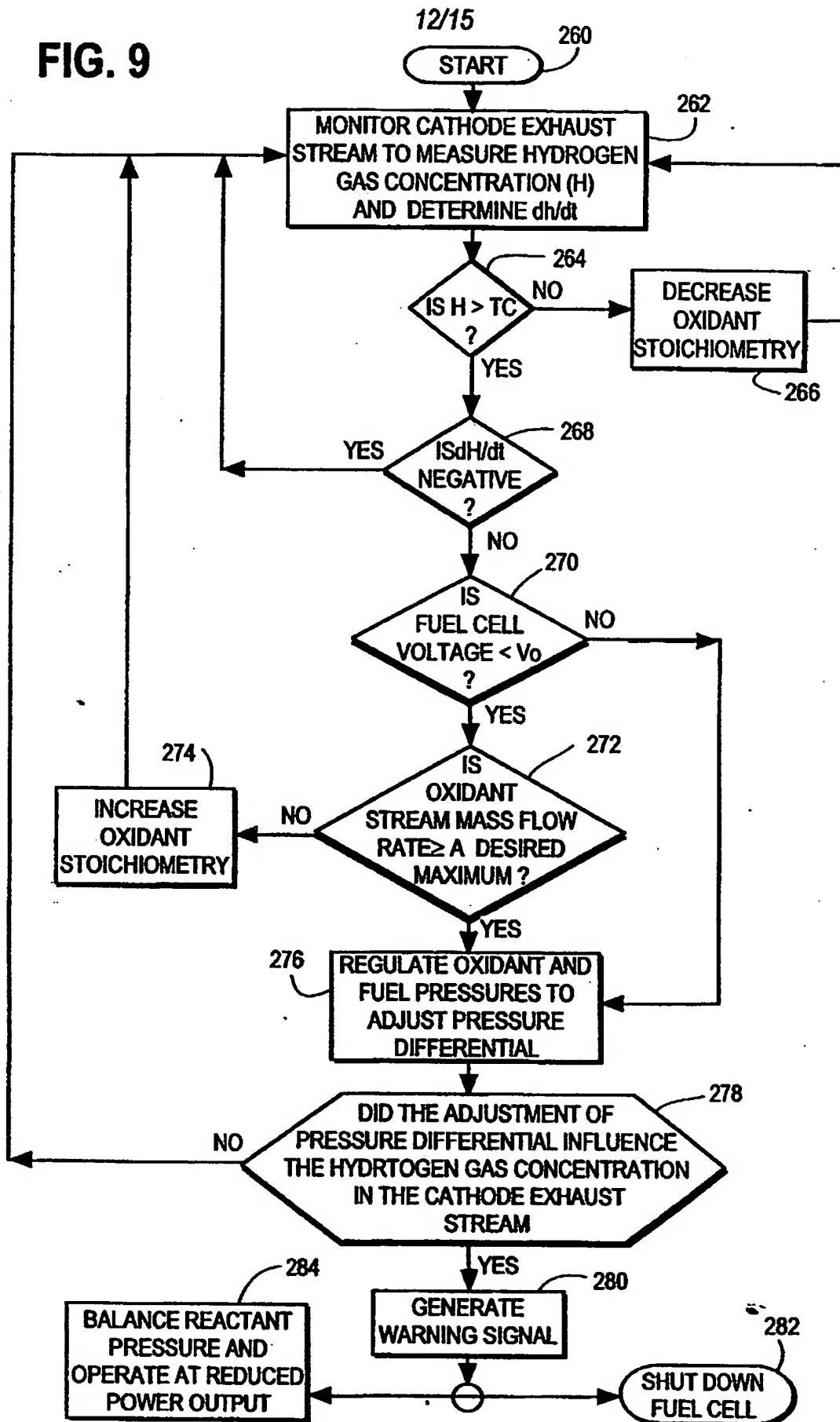


FIG. 9



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FIG. 10

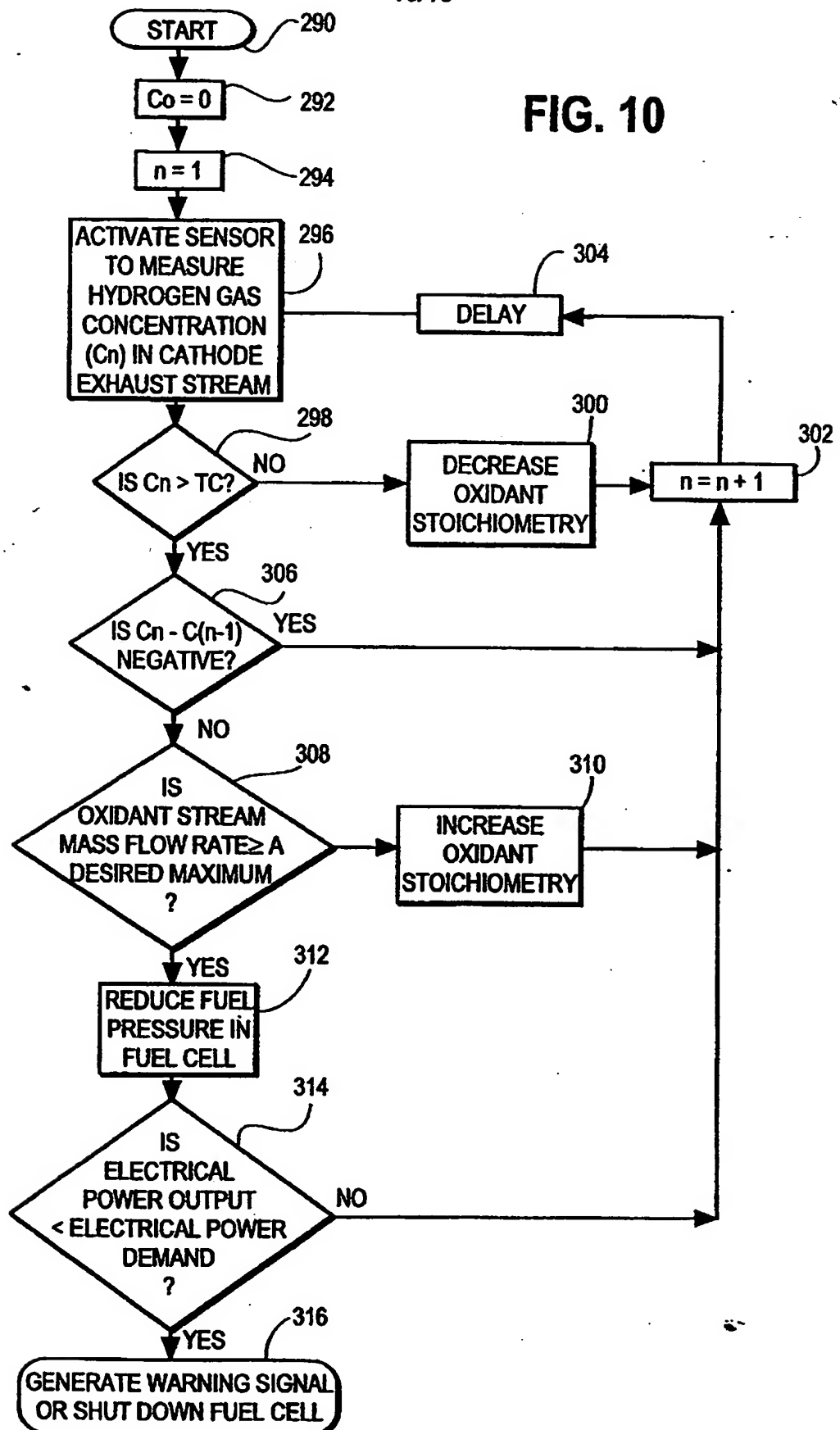
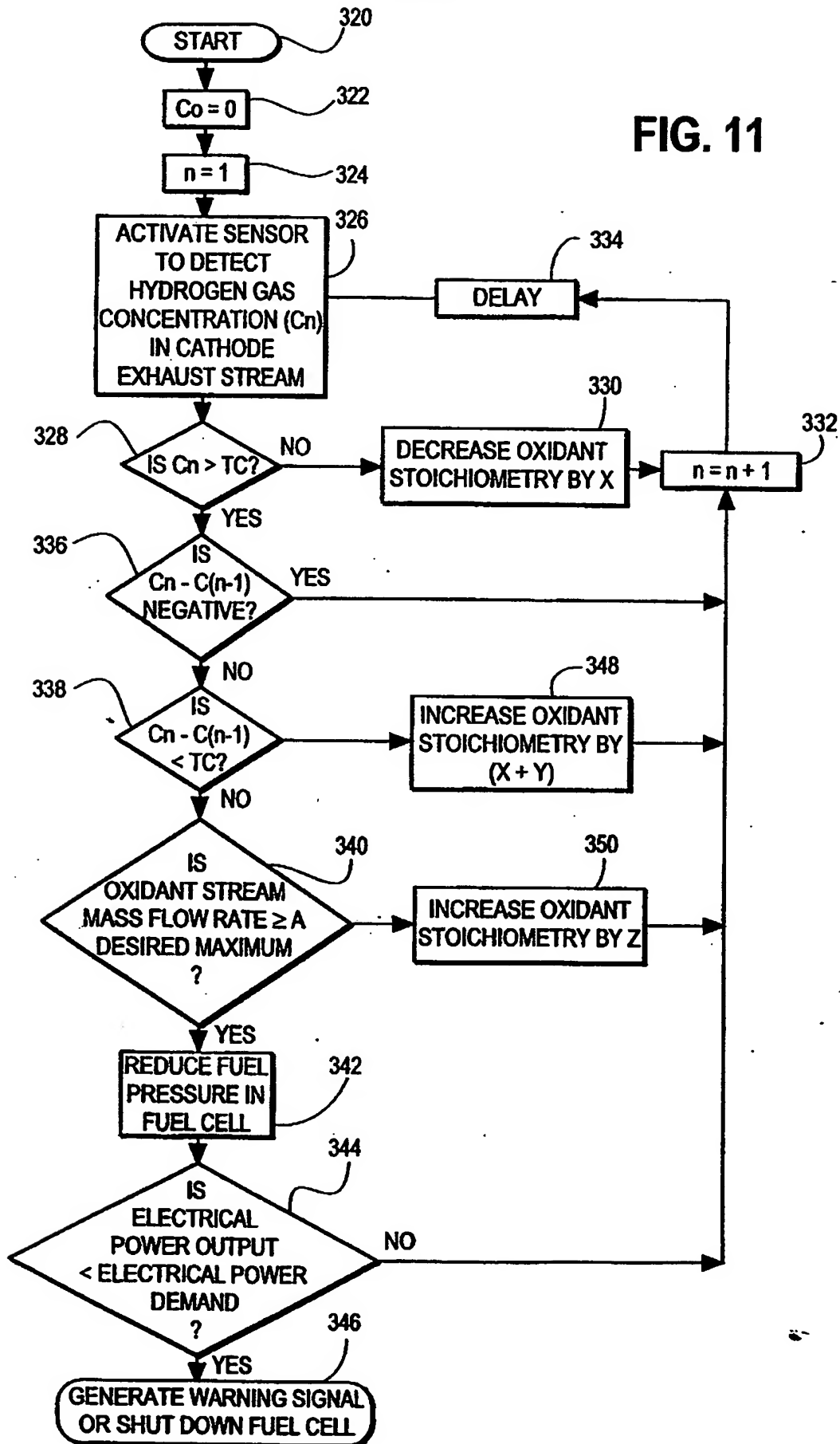
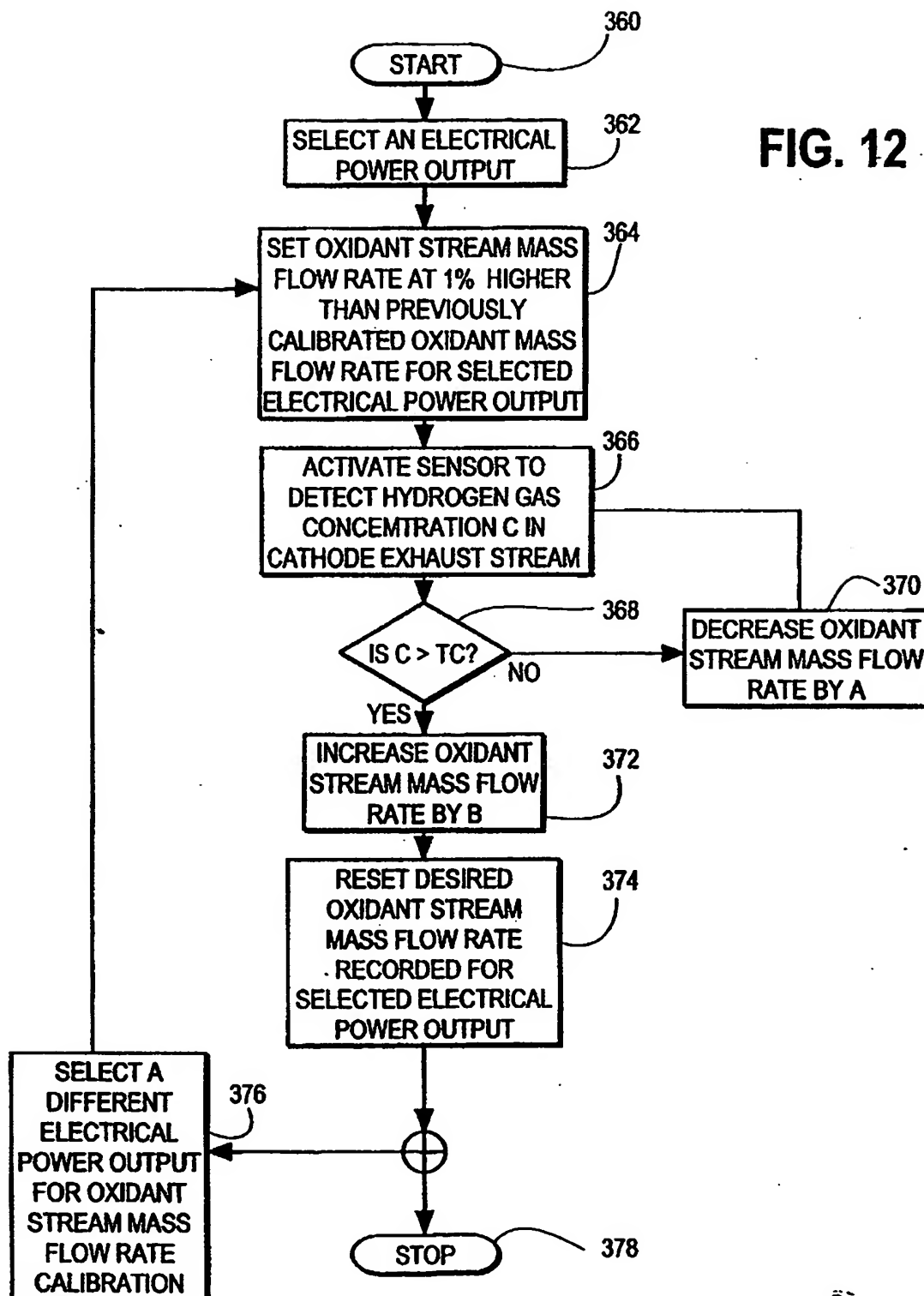


FIG. 11



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FIG. 12





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(71) Applicant (for all designated States except US): BALLARD POWER SYSTEMS INC. [CA/CA]: 9000 Glenlyon Parkway, Burnaby, British Columbia V5J 5J9 (CA).

(72) Inventors; and

(75) Inventors/Applicants (for US only): BOEHM, Gustav [DE/DE]: Zur Forelle 34, 88662 Ueberlingen (DE). WILKINSON, David, P. [CA/CA]: 1391 Coleman Street, North Vancouver, British Columbia V7K 1W4 (CA). KNIGHTS, Shanna [CA/CA]: 5376 Forest Street,

Burnaby, British Columbia V5G 1X2 (CA). SCHAMM, Reinhold [DE/DE]: Muensterlinger weg 12, 88179 Stetten (DE). FLETCHER, Nicholas, J. [CA/CA]: 3464 Point Grey Road, Vancouver, British Columbia V6R 1A5 (CA).

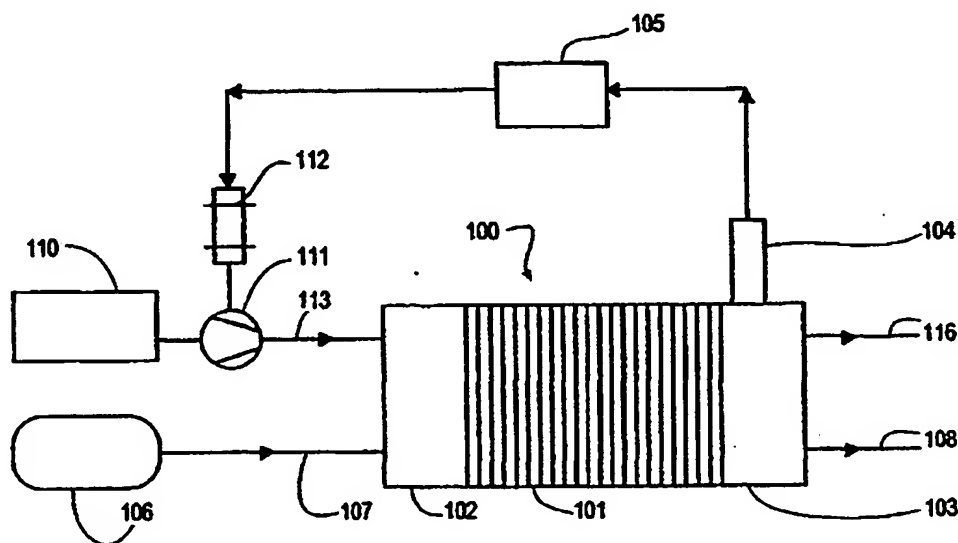
(74) Agent: DE KOCK, Elbie, R.: Russell Reyneke, Two Bentall Centre, Suite 700, 555 Burrard Street, Vancouver, British Columbia V7X 1M8 (CA).

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[Continued on next page]

(54) Title: METHOD AND APPARATUS FOR OPERATING A FUEL CELL



(57) Abstract: The present invention relates to improving the overall efficiency of a fuel cell system by reducing parasitic power consumption. In particular, efficiency is improved by controlling the supply of oxidant to reduce excess oxidant stream flow by operating the fuel cell system with an oxidant stoichiometry between about one and two. A controller is programmed to decrease oxidant stoichiometry until oxidant starvation is detected or until oxidant stoichiometry is about one. When oxidant starvation is detected, the oxidant stoichiometry is increased until oxidant starvation is no longer detected. The fuel cell system employs a sensor for detecting an operational characteristic such as voltage output, or oxygen or hydrogen concentration in the cathode exhaust stream. The controller uses the operational characteristic to calculate oxidant stoichiometry or to determine when there is oxidant starvation at the cathode.

WO 01/43216 A3

# INTERNATIONAL SEARCH REPORT

International Application No

PCT/CA 00/01426

## C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	<p>US 5 366 821 A (MERRITT ROBERT D ET AL) 22 November 1994 (1994-11-22)</p> <p>figure 4 column 5, line 10 - line 49 column 6, line 3 - line 24 column 7, line 60 - column 8, line 16 column 9, line 65 - column 10, line 34 claims 1-3,9</p>	<p>1,2,12, 13,15, 17, 47-49, 51-53</p>
A	<p>EP 0 827 226 A (GEN MOTORS CORP) 4 March 1998 (1998-03-04)</p> <p>column 2, line 25 - column 3, line 42 column 7, line 16 - line 26 column 8, line 6 - line 26 claim 2</p>	<p>1,5,7, 12,13, 17-20, 22,25, 26,30, 34-36, 39, 47-49, 51,55</p>
P,A	<p>WO 00 02282 A (BALLARD POWER SYSTEMS ;LAURITZEN MICHAEL V (CA); WILKINSON DAVID P) 13 January 2000 (2000-01-13)</p> <p>page 9, line 18 - line 32 page 10, line 14 - line 31 page 16, line 25 - page 17, line 26 page 20, line 1 - line 29 page 23, line 3 - line 4 page 27, line 18 - line 21 page 28, line 6 - line 27</p>	<p>1,2,12, 13, 15-17, 47-54, 58,59</p>



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